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Weston (Roy F.), Inc., West Chester, PA

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EMERGING TECHNOLOGY ASSESSMENT OF PHOSTRIP, A/O, AND BARDENPHO PROCESSES FOR BIOLOGICAL PHOSPHORUS REMOVAL

by

Weston, Inc.
Designers-Consultants
West Chester, Pennsylvania 19380

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Project Officer

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16. ABSTRACT

An engineering evaluation of three proprietary processes for biological removal of phosphorus from municipal wastewater was conducted. The report presents for each process:
Technology Description;
Technology Evaluation;
Development Status;
Equivalent Technologies Comparison;
Assessment of National Impact;
Cost Considerations; and
Recommendations.

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FOREWORD

The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water systems. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. The Clean Water Act, the Safe Drinking Water Act, and the Toxics Substances Control Act are three of the major congressional laws that provide the framework for restoring and maintaining the integrity of our Nation's water, for preserving and enhancing the water we drink, and for protecting the environment from toxic substances. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Water Engineering Research Laboratory is that component of EPA's Research and Development program concerned with preventing, treating, and managing municipal and industrial wastewater discharges; establishing practices to control and remove contaminants from drinking water and to prevent its deterioration during storage and distribution; and assessing the nature and controllability of releases of toxic substances to the air, water, and land from manufacturing processes and subsequent product uses. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

The innovative and alternative technology provisions of the Clean Water Act of 1977 (PL 95-217) provide financial incentives to communities which use wastewater treatment alternatives that reduce costs or energy consumption over conventional systems. Some of these technologies have been only recently developed and are not in widespread use in this country. In an effort to increase awareness of the potential benefits of such alternatives and to encourage their implementation where applicable, the Water Engineering Research Laboratory has initiated this series of Emerging Technology Assessment reports. This document discusses the applicability and economic feasibility of utilizing biological processes for the control of phosphorus for municipal wastewater treatment.

Francis T. Mayo, Director
Water Engineering Research Laboratory

ABSTRACT

This technology assessment addresses three proprietary processes (namely PhoStrip, A/O, and Bardenpho) for biological phosphorus removal from municipal wastewaters. These processes are used as alternatives to the conventional method of treatment by activated sludge with chemical addition for phosphorus precipitation. The objective of this report is primarily to provide guidance to those individuals involved with reviewing new processes as part of the Innovative and Alternative Technology program.

PhoStrip, A/O, and Bardenpho processes were all developed in the early 1970's based on the ability of the biological system to provide enhanced or the so called "luxury" uptake, which involves the mechanism of phosphorus release by microorganisms under anaerobic conditions, followed by cellular phosphorus uptake under aerobic conditions. These three systems are different with respect to their specific process design and to their ability to provide phosphorus removal, as well as various degrees of nitrogen removal. The PhoStrip process employs sidestream (i.e., a portion of the return sludge) treatment in an anaerobic contact tank where biologically-bound phosphorus is released to the aqueous medium, and the supernatant liquor is treated with lime to precipitate inorganic phosphorus as calcium hydroxyapatite. Both the A/O and Bardenpho processes involve mainstream (influent flow plus sludge recycle) anaerobic treatment to pre-condition the system for phosphorus removal via waste activated sludge.

The A/O process can be designed for phosphorus removal without nitrification by use of anaerobic/oxic stages, or for phosphorus removal with nitrification by use of anaerobic/anoxic/oxic stages plus additional internal mixed liquor recycle from the oxic to the anoxic stage. The Bardenpho system is a five-stage (anaerobic/anoxic/aeration/anoxic/reaeration) process designed to provide both phosphorus and total nitrogen removal.

The development status of these processes (including a list of pilot studies and full-scale installations), process theory, capabilities, and design considerations are addressed in this report.

Related capital, O&M, and total present worth costs for these three processes, as well as for baseline technology of coventional activated sludge (one, two, or three-stage system depending on the degree of nitrogen removal required) with alum addition, were estimated to provide a reasonable basis for alternative comparison. Based on these estimates and assumptions of the total present worth costs, the three proprietary processes are found to be cost-effective and particularly applicable under the following conditions:

- PhoStrip process for effluent residual total phosphorus for large treatment plants.
- A/O process for effluent residual total phosphorus at all plant sizes.
- Modified A/O process for effluent residual total phosphorus of 2 mg/L and 1 mg/L ammonia nitrogen at all plant sizes.
- Bardenpho process for effluent residual total phosphorus of 2 mg/L and total nitrogen of about 3 mg/L at all plant sizes.

Market potential for these three processes (based on a needs survey in the U.S.), and their costs and energy impacts are addressed in the report. Further research and development efforts and potential areas for process modifications are also identified.

Appendix C contains the response of the three proprietary firms to this report.

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  Mr. Tony Kish
- Air Products and Chemicals, Inc. - Dr. David J. Krichten
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- EIMCO Process Machinery Division
  of Envirotech Corp. - Mr. David DiGregorio
- Dr. H. David Stensel (University of Utah)

SECTION 1

TECHNOLOGY DESCRIPTION

INTRODUCTION

For the past two decades, phosphorus has been recognized as a major limiting factor (along with nitrogen) in the control of eutrophication due to excessive algae and aquatic vegetative growth in streams and lakes. In response to this effect, pollution control agencies have instituted stringent limitations controlling nutrient discharge into receiving waters. Examples are the Great Lakes regions, the Florida Tampa Bay region, Lake Tahoe, and the Chesapeake Bay area (1). Typical effluent standards have been 1 mg/L and 3 mg/L for phosphorus and total nitrogen, respectively. Less stringent requirements are also adopted in various localities to meet water quality standards.

Since the early 1970's, chemical precipitation with either alum, ferric chloride, or lime has been the widely used as a demonstrated technology for phosphorus removal (2). Where possible, steel mill waste pickle liquor has provided a relatively inexpensive chemical source for phosphorus precipitation, although it may also contain other undesirable heavy metals. The disadvantages of chemical precipitation treatment for phosphorus removal are chemical costs, chemical handling and storage requirements, increased sludge production, and related sludge handling and disposal costs.

Prior to the present application of specifically designed biological phosphorus removal systems, a series of studies and full-scale plant observations on biological phosphorus removal had been reported. In 1955, Greenburg et al. (3) proposed that activated sludge could take up phosphorus at a level beyond its normal microbial growth requirements. Srinath et al. (4) reported in 1959 that soluble phosphorus in mixed liquor (aqueous phase) decreases rapidly to below 1 mg/L under varying conditions of aeration. However, Levin and Shapiro (5) in 1965 were the first to associate excess biological phosphorus removal, now called "luxury uptake," with anaerobic/aerobic sequencing of biological treatment systems, which is currently the accepted mechanism. This led to intensive studies of the possible application of this phenomenon for removal of phosphorus in activated sludge plants (6, 7, 8, 9, 10). It appeared that all the plants that successfully removed phosphorus were high-rate, non-nitrifying, plug-flow type activated sludge plants. By the early 1970's, three distinct proprietary biological phosphorus removal processes had been developed; namely, the PhoStrip process by Levin et al. (11, 12, 13), the Bardenpho process by Barnard of South Africa (14, 15), and the A/O process by Air Products and Chemicals, Inc. (16, 17). These three commercial biological phosphorus removal processes are currently patented and marketed in the United States by the following companies:

- PhoStrip - Biospherics, Inc.
- A/O - Air Products and Chemicals, Inc.
- Bardenpho - EIMCO Process Machinery Division of Envirotech Corporation

In addition to the three major proprietary processes discussed in this report, a number of other modifications to the biological phosphorus removal system have been proposed. They include:

- The UTC (University of Capetown) process described by Siebritz, Ekama and Marais (18) for application to wastewaters with relatively high total Kjeldahl nitrogen to chemical oxygen demand (TKN/COD) ratios.
- The "safe" design optimization approach proposed by Mulbarger and Prober (19), which can be various combinations of primary chemical treatment, anaerobic and aerobic contacting as in the A/O, PhoStrip with lime addition, and metal salts addition in the aeration basin for polishing phosphorus to low levels.
- The biological phosphorus removal with "roughing" chemical treatment proposed by Stensel (1), which is a modified anaerobic contactor design similar to a combination of the Bardenpho or A/O with the PhoStrip system.

These modified processes can be applicable to certain specific cases; however, they are not included in the technical assessment within this report due to the complexity of the subject and their limited available development data.

The Clean Water Act (PL 95-217) mandated that an analysis and evaluation of innovative and alternative technologies be conducted during the development of federally-funded wastewater management projects (21, 22). This requirement, administered through the U.S. Environmental Protection Agency's (EPA) Construction Grants Program, has encouraged the development of several new treatment processes having potential for application in municipal wastewater treatment practice. In order to assess the status of development and the capabilities of these "emerging" technologies, EPA has initiated a series of technology assessments for evaluating these processes. This technology assessment report is prepared to evaluate the three patented processes for biological phosphorus removal, which are currently gaining in acceptance and applications.

TECHNOLOGY DESCRIPTIONS

PhoStrip Process

The PhoStrip process was first proposed by Gilbert Levin in 1965 (5, 6) and is currently marketed by Biospherics, Inc. This process is an activated sludge process that takes advantages of "luxury" phosphorus uptake and anaerobic phosphorus release. A schematic flow diagram of the PnoStrip process is presented in Figure 1. This process differs from conventional activated sludge in that a portion of the return sludge is subjected to "phosphorus stripping" by holding the sludge under anaerobic conditions in a stripper tank. The solids retention time (SRT) in this tank typically ranges from 8 to 12 hours. During this anaerobic period, phosphorus is released and is elutriated from the sludge in the stripper tank with a stream that is low in phosphorus content. This stream may either be the overflow from the chemical treatment tank (reactor clarifier) as is shown in Figure 1, or primary effluent. The phosphorus-rich overflow from the stripper tank passes continuously to the chemical treatment tank where lime is added for phosphorus precipitation.

Because of the flexibility of the percent of return sludge that can be subjected to anaerobic conditions for different detention times in the stripper tank, a wide range of phosphorus removal can be achieved. Control of the side-stream permits phosphorus removal to be divided between stripper supernatant and waste activated sludge (13).

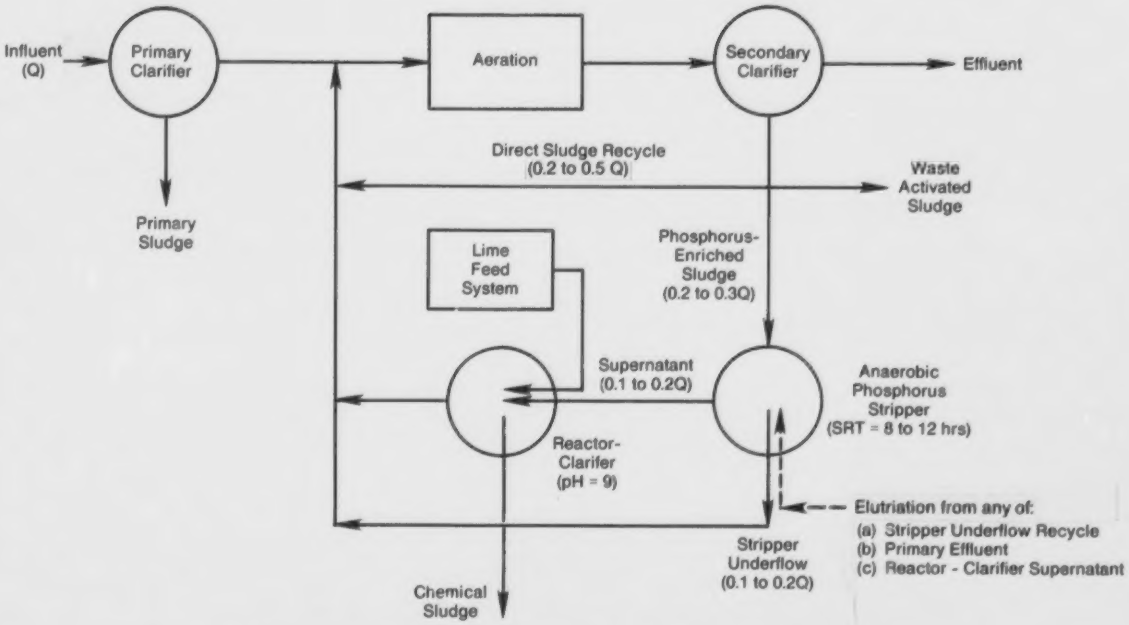
Influent (Q)
Primary Clarifier
Primary Sludge
Aeration
Secondary Clarifier
Effluent
Direct Sludge Recycle (0.2 to 0.5 Q)
Waste Activated Sludge
Lime Feed System
Phosphorus-Enriched Sludge (0.2 to 0.3Q)
Supernatant (0.1 to 0.2Q)
Anaerobic Phosphorus Stripper (SRT = 8 to 12 hrs)
Reactor-Clarifer (pH = 9)
Elutriation from any of:
(a) Stripper Underflow Recycle
(b) Primary Effluent
(c) Reactor - Clarifier Supernatant
Stripper Underflow (0.1 to 0.2Q)
Chemical Sludge

Figure 1. PhoStrip process flow diagram.

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A/O Process (Anaerobic/Oxic)

The A/O process was developed by Air Products and Chemicals, Inc. for the removal of phosphorus and/or nitrogen from wastewater (16, 17). The A/O process is a single-sludge, suspended growth system that can combine anaerobic, anoxic[1], and aerobic sections in sequence. Figure 2(a) is a schematic representation of the A/O process for phosphorus removal. The process can be designed for phosphorus removal with or without nitrification and denitrification. All sections are partitioned into several hydraulic stages to approach plug-flow and prevent back-mixing. Typically, for removal of phosphorus, three anaerobic stages are followed by three or more aerobic or oxic stages. Recycled sludge from the secondary clarifier is mixed with either raw wastewater or primary effluent in the anaerobic section so that there is "sorption" of BOD by the organisms, with accompanying phosphorus release necessary for biological phosphorus removal. The anaerobic section is covered and equipped with mechanical mixers for mixing but not aeration.

The oxic stage, essential for the metabolism of BOD and uptake of the phosphorus released in the anaerobic stage, may be aerated with either air or oxygen. Phosphorus is removed from the system in the waste sludge, which may contain 4- to 6-percent phosphorus by dry weight. Effluent phosphorus concentrations are dependent on sludge wasting, which in turn is controlled by the plant's operating solids residence time (SRT).

When necessary, nitrification can be accomplished in the oxic section by operation at a properly selected solids residence time and organic loading suitable for growth of nitrifying bacteria. When denitrification is further required, the anoxic section is included between an anaerobic and oxic section as shown in Figure 2(b). The anoxic section is deficient in dissolved oxygen, but chemically-bound oxygen in the form of nitrate or nitrite is introduced by recycling nitrified mixed liquor from the oxic section back to the anoxic section.

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[1] The term "anaerobic" refers to environments that have no measurable concentrations of either dissolved oxygen or oxidized nitrogen in the form of nitrate or nitrite; "anoxic" refers to environments that have no dissolved oxygen, but can have oxidized nitrogen present.

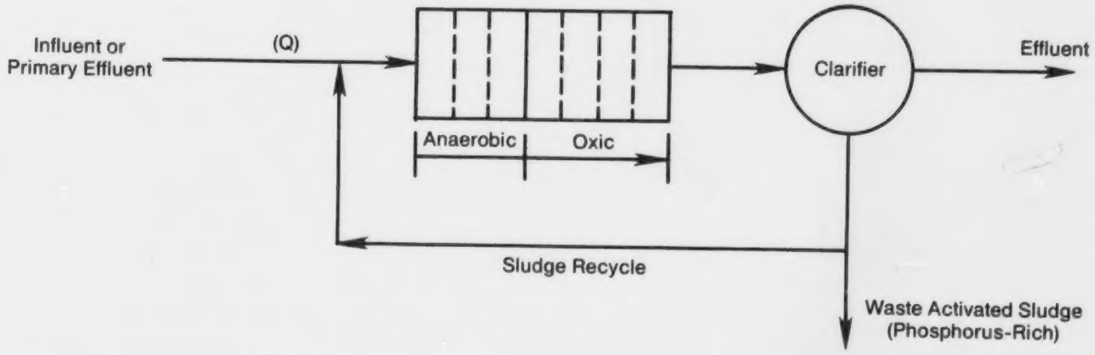

Figure 2(a). **A/O process flow diagram for phosphorus removal.**

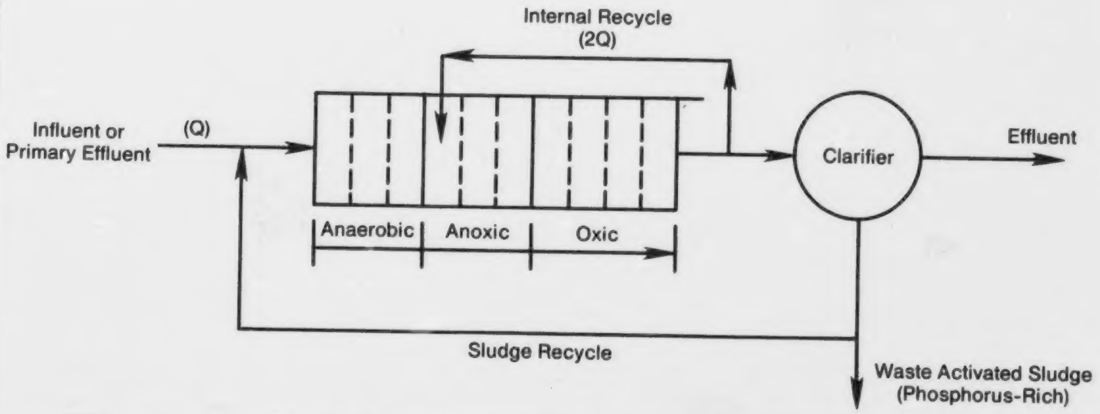

Figure 2(b). **A/O for phosphorus removal with nitrification/denitrification.**

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Bardenpho Process

The Bardenpho process was first investigated in Pretoria, South Africa by James Barnard in the early 1970's (14). Bardenpho stands for Barnard-denitrification-phosphorus, an activated sludge process designed to accomplish both biological phosphorus uptake and nitrogen removal. The process is patented by the South African Inventions Development Corporation and licensed to Envirotech Corporation for marketing in the United States. The Bardenpho process is very similar to the previously described A/O process, except there is an additional anoxic and a reaeration section at the tail end.

As shown in Figure 3, two anoxic stages are used to accomplish high levels of biological nitrogen removal by denitrification. An anaerobic stage is added ahead of the original four-stage Bardenpho nitrogen removal system to create anaerobic-aerobic contacting conditions necessary for biological phosphorus uptake. Return activated sludge, separated from the clarifier, is mixed with the influent wastewater prior to the anaerobic contactor, which is to initiate luxury phosphorus uptake by first releasing phosphate. Mixed liquor from the anaerobic contactor then flows into the first anoxic denitrification zone where it is mixed with an internally recycled mixed liquor from the aerobic nitrification zone. In the first anoxic denitrification zone, nitrate is reduced to nitrogen gas using soluble organic matter in the wastewater as a carbon source. The mixed liquor then flows into the aerobic nitrification zone where luxury phosphorus uptake, ammonia oxidation, and additional BOD removal occurs. Following the aerobic nitrification zone, a second anoxic zone provides additional denitrification, which is designed to remove additional nitrate and minimize nitrate feedback to the anaerobic contactor. The reaeration zone provides oxidation of remaining ammonia and raises dissolved oxygen levels for effluent discharge.

Phosphorus is removed from the system in the waste sludge, which may contain 4- to 6-percent phosphorus by dry weight. Depending on the relative amounts of phosphorus, BOD, and nitrogen in the influent, low levels of phosphorus (less than 1 mg/L) can be achieved in the effluent. For weaker wastewaters or high influent phosphorus concentrations, a small amount of chemicals, such as alum or ferric salts, are added to polish the effluent phosphorus to below 1 mg/L, if required. Because of the liquid detention times and SRT required for nitrification and denitrification, a relatively high-quality effluent in terms of BOD, suspended solids, and ammonium nitrogen concentrations is possible. The resultant SRT provides an aerobically-stabilized sludge that has been disposed of without further stabilization (1).

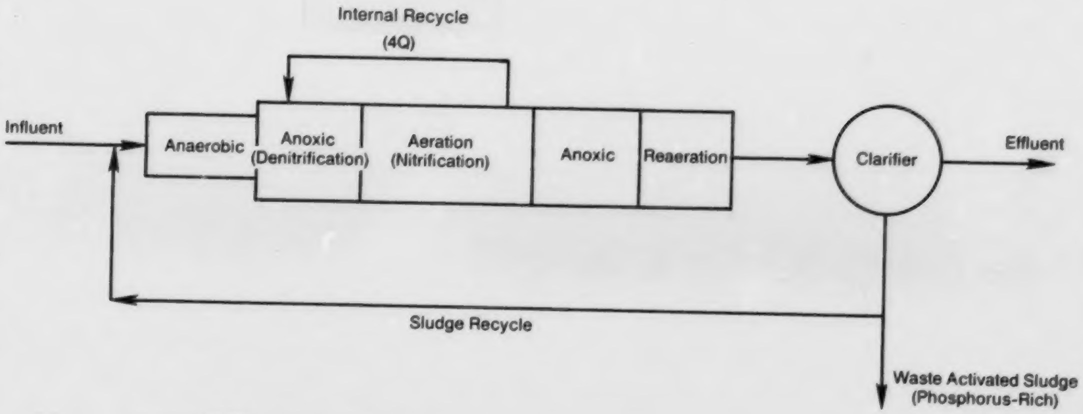

Figure 3. Bardenpho process flow diagram.

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SECTION 2

TECHNOLOGY EVALUATION

PROCESS THEORY

Phosphorus in raw wastewaters exists in three forms: orthophosphate (PO_4), poly-phosphate (P_2O_7), and organic phosphorus (47). The ortho-phosphorus can be readily assimilated by microorganisms, and the poly- and organic phosphorus forms are usually hydrolyzed by microorganisms to the ortho form. Phosphorus is an important element for microorganisms due to its use in energy transfer and for cell components such as phospholipids, nucleotides, and nucleic acids. The amount of phosphorus removed due to sludge wasting may be in the range of 10 to 30 percent of the influent amount for typical secondary treatment employing the activated sludge process.

The PhoStrip, A/O, and Bardenpho processes were all developed in the early 1970's by utilizing essentially the same mechanism of enhanced biological phosphorus removal (or the so-called "luxury" uptake) in activated sludge systems, which is created by cyclic stressing of the system to anaerobic (i.e., absence of molecular oxygen, nitrate, or nitrite) and aerobic conditions. This mechanism takes advantage of the fact that phosphorus is released by microorganisms under anaerobic (starved) conditions and subsequently incorporated to a higher cellular content (luxury) under aerobic conditions.

The biological phosphorus and BOD removal due to anaerobic-aerobic contacting in the A/O process is depicted in Figure 4. The A/O process initially mixes the full forward influent and recycle sludge under anaerobic conditions to influence selection of microbial population favorable to such phosphorus removal mechanism (17). Phosphorus is removed from the system through wasting of activated sludge that is rich in phosphorus content. The phosphorus levels in the waste activated sludge from the A/O process typically reach 4 to 6 percent by dry weight, as compared to 2 to 3 percent in conventional activated sludge.

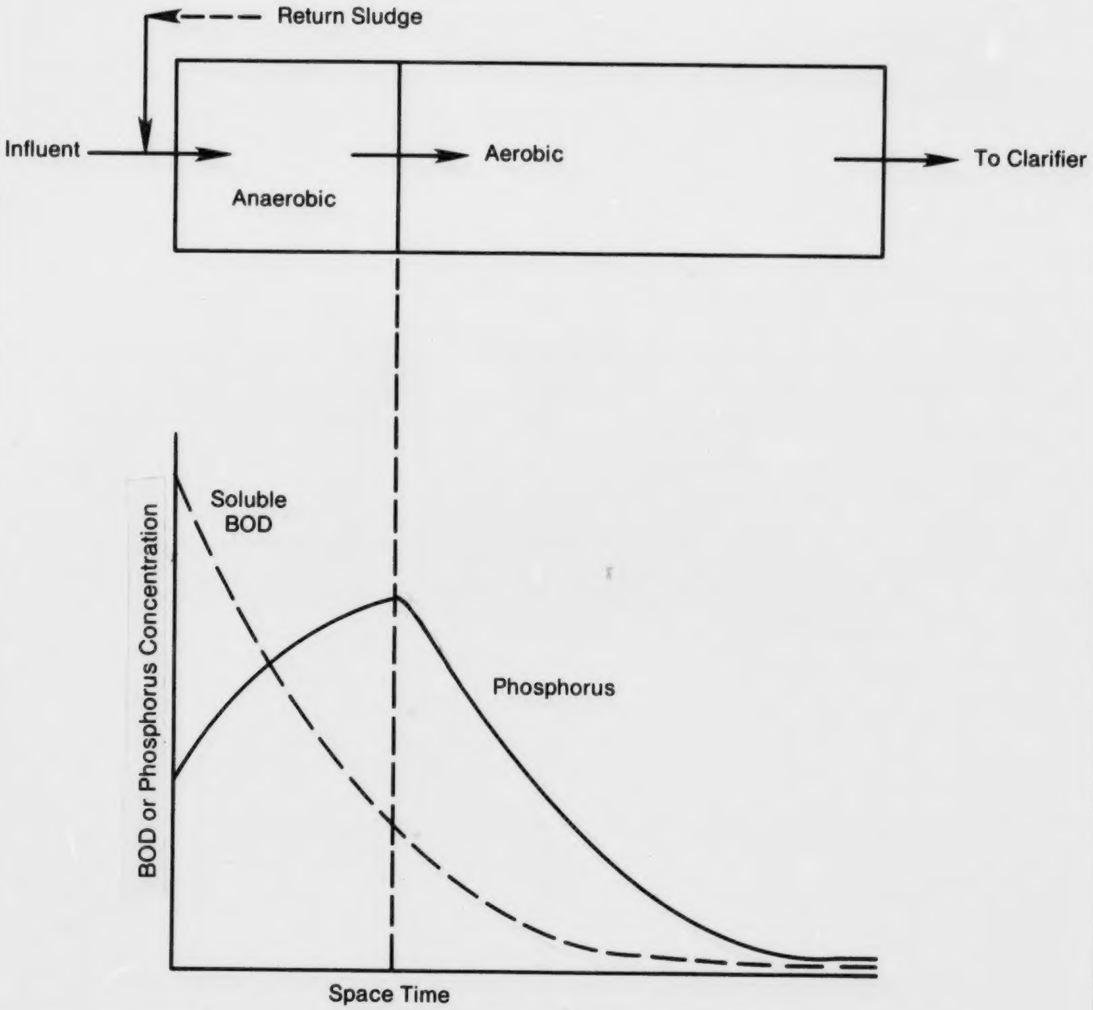

Figure 4. Biological phosphorus and BOD removal due to anaerobic - aerobic contacting (Adopted from Ref. 17).

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In the case of the PhoStrip process, a portion of the return activated sludge is routed to an "anaerobic stripper" tank where the microorganisms release soluble phosphorus. The stripper tank supernatant, which is only a fraction of the total wastewater flow, needs proportionally lower amounts of lime to precipitate the phosphorus in this flow. The supernatant and lime mixture may then be routed to the primary clarifier or a separate reactor-clarifier for removal of the precipitated sludge. The phosphorus-depleted sludge from the stripper is returned to the aeration basin, where the microorganisms take up phosphorus under aerobic conditions (13). Part of the phosphorus is also removed from the system through the waste activated sludge route. The relative amounts of phosphorus removed through the two exit points can depend on wastewater characteristics (particularly the relative concentrations of BOD and phosphorus in the influent) as well as design and operation of a specific system.

In the Bardenpho process, Barnard (14) found that higher-level phosphorus removal from wastewater occurred during aeration of sludge that was subjected to anaerobic contacting; thus, he added an anaerobic contacting stage ahead of the four-stage (anoxic-aeration-anoxic-reaeration) system originally devised for nitrogen removal. Barnard also found that nitrates in the recycle flow to the anaerobic zone could prevent phosphorus release and reduce the high levels of phosphorus uptake in the aerobic zone; thus, the internal recycle of mixed liquor from the aerobic to the anoxic zone (see Figure 3) to remove the nitrate is also important from the standpoint of maintaining anaerobic conditions in the first stage. As in the case of A/O, the full forward influent flow and recycle sludge are subjected to anaerobic treatment, and the phosphorus is removed from the system through sludge wasting. Thus, of the three proprietary systems, PhoStrip is a sidestream treatment process, while A/O and Bardenpho are mainstream treatment processes.

The anaerobic-aerobic staging apparently results in the selection of a biological population that is capable of achieving phosphorus removal. The actual mechanism for the phosphorus storage and release is not fully known, nor is the basis for the phosphorus removal population selection. This is partly due to the complexity of the many factors involved, and to the lack of complete quantitative fundamental analysis of the biological phenomena. The following lists the various empirical observations reported for the occurrence of biological phosphorus removal (1):

- Phosphorus release occurs under anaerobic contacting, with mixed liquor soluble phosphorus reported in the range of 20 to 40 mg/L.

- Phosphorus uptake occurs rapidly under subsequent aerobic conditions to produce low mixed liquor soluble phosphorus concentrations.

- The increased phosphorus taken up appears to be stored as polyphosphates in the cell, or contained in volutin granules within the cell. The volutin granules contain lipids, protein, RNA, and magnesium, in addition to polyphosphates. Volutin is used for nucleic acid synthesis and may be released as orthophosphate to meet metabolic requirements of the cell (5, 48, 49, 50, 51).

- The synthesis and degradation of poly-beta-hydroxybutyrate (PHB), which is an intracellular carbon storage product, can play a role in the biological phosphorus removal (52 through 60).

- *Acinetobactor* (a gram-negative, aerobic bacteria) has been frequently found in biological phosphorus removal systems and is known to store polyphosphate (61, 50, 53, 54, 55). However, glucose is not assimilated by *Acinetobactor*. Other types of polyphosphate-storing bacteria, including certain gram-positive species, *Aeromonas*, *Pseudomonas*, and facultative bacteria, have also been found to exist in biological phosphorus removal systems (49, 62, 63).

- Significant levels (over 70 percent) of influent soluble BOD could be taken up by the microorganisms in the initial anaerobic stage. Aeration-stage oxygen uptake rates are lower in anaerobic-aerobic systems than in conventional activated sludge systems. This can be due to the accumulation of storage products such as PHB within the cells during the anaerobic stage, thereby extending the period of oxidation of the carbon source (57, 58).

- The presence of nitrates or oxygen in the anaerobic stage will prevent phosphorus release and subsequent biological phosphorus removal. Methods available to mitigate this effect include:

    - Feeding high BOD strength wastewater to the system to rapidly deplete any dissolved oxygen.

    - Avoiding any recycling of nitrified effluent or sludge containing nitrate back to the anaerobic stage.

- Providing removal of nitrate by separate-stage denitrification, if nitrification is also required.

- Extending the period of anaerobic contacting, if necessary, to provide residence time for denitrification.

PROCESS CAPABILITY AND LIMITATIONS

All three proprietary processes have been demonstrated as capable of removing phosphorus from the 4 to 12 mg/L range normally found in municipal wastewaters (20) down to the 1 to 2 mg/L ranges as total phosphorus (TP). It is important to consider effluent limitations in each specific case to determine the applicability of each of these processes. For example, the Great Lakes and Florida-Tampa Bay Region call for effluent limitations of 1 mg/L as TP, while some areas in South Africa have a standard of less than 1 mg/L of ortho-phosphate ($O\text{-}PO_4$) as P. Since these processes are often "marginal" in producing effluent quality of less than 1 to 2 mg/L as TP, or 1 mg/L as $PO_4\text{-}P$, other provisions, such as supplemental mineral addition to precipitate residual phosphorus and/or effluent filters, may be necessary unless the reliability of the selected process is demonstrated by treatability tests or pilot-plant data for a specific case.

PhoStrip processes can consistently produce effluent soluble phosphorus of less than 1.0 mg/L as $PO_4\text{-}P$, and are capable of producing total phosphorus of 1 mg/L on an average basis (see Table 1 in Section 3). However, due to variability in flow and wastewater characteristics, and to other operational reasons, excursions above the 1 mg/L TP in treated effluent are not uncommon. Seven of the existing plants (those shown with an asterisk (*) in Table 1) have been provided effluent filters to assure that effluent total phosphorus of 1 mg/L can be met. The PhoStrip process is particularly applicable to cases where only phosphorus removal is required (i.e., without nitrification). The process, without modification, is not suitable for application when hydraulic detention in the aeration basin exceeds 10 hours, or when significant nitrification occurs in the system. When nitrification is necessary, PhoStrip can be used in conjunction with the first stage of a two-stage activated sludge process; or, if a single-stage activated sludge system is used, certain modifications, such as increase of anaerobic contact time, would have to be made to compensate the effect from nitrate.

The A/O process can be used for phosphorus removal with or without nitrification. Concentrations of total phosphorus in the treated effluent are usually in the range of 1.5 to 3.0 mg/L (see Table 2 in Section 3). Since significant amounts of effluent phosphorus are associated with the suspended solids, effluent filters would become necessary if total phosphorus at 1 mg/L is to be met. It is possible that the A/O process can be designed also for denitrification. However, operations at Largo showed that only partial denitrification was achieved. The capability of the A/O process to provide phosphorus removal, as well as complete nitrificacation/denitrification, remains to be demonstrated. It should be noted that phosphorus-rich waste activated sludge is generated from the A/O process. The sludge should be further stabilized to remove degradable portions of volatile solids by either aerobic or anaerobic digestion. In particular, when anaerobic digestion is used, the digested liquor would contain high concentrations of phosphorus, and it should not be returned to the front end of the A/O system without chemical treatment to precipitate the phosphorus. Air Products estimates that for each 37,850 m^3 (10 million gallons) of wastewater treated, 1.0 to 1.5 tons (2,000 to 3,000 lb) of lime are required for anaerobically-digested sludge, and 0.33 ton (660 lb) of lime is required for aerobically-digested sludge (17).

The Bardenpho process is applicable when removal of both the phosphorus and total nitrogen is necessary. This process is not normally used when only phosphorus removal is required. The capability of the Bardenpho process to consistently produce total phosphorus of less than 2 mg/L, or soluble phosphate of less than 1 mg/L as P, without supplemental mineral addition, remains to be demonstrated (see Table 3 in Section 3). Effluent filters would probably be needed if total phosphorus in the effluent is to be reduced to less than 1 mg/L. Since solids residence time (SRT) in the Bardenpho process is typically maintained near 20 days and can be as long as 40 days, the excess sludge wasted from the system is reasonably well stabilized.

DESIGN CONSIDERATIONS

Since PhoStrip, A/O, and Bardenpho are all proprietary processes, respective consultation from Biospherics, Air Products, or EIMCO should be sought when designing a specific biological phosphorus removal system. Typical design parameters and other considerations important to each of the three processes are presented in the following paragraphs.

PhoStrip Process

Biospherics (13) has developed extensive empirical design relationships covering various factors that affect performance of a PhoStrip system. The process can operate with conventional (plug flow), complete-mix, tapered, step aeration, modified, and pure-oxygen activated sludge modes without interfering with required BOD and suspended solids removal objectives. With modification, PhoStrip is also applicable to contact stabilization and extended aeration modes. Successful PhoStrip operations have been observed to occur under the following conditions:

- Influent BOD_5 = 70 to 300 mg/L.
- Influent TP = 3 to 20 mg/L.
- Wastewater temperature = 10 to 30°C.
- Secondary clarifier NO_3-N plus NO_2-N = 3 to 30 mg/L. The high end of this range requires denitrification consideration.
- Hydraulic detention time in aeration basin = 1 to 10 hours.
- MLSS = 600 to 5,000 mg/L.

Typical PhoStrip design parameters are as follows:

- Refer to Figure 1.
- Sidestream return sludge flow to be treated = 0.2 to 0.3 Q.
- Anaerobic phosphorus stripper sludge retention time = 8 to 12 hours (elevated NO_2/NO_3-N concentrations require a 50 percent increase in SRT).
- Stripper SWD = 6.1 m (20 ft).
- Stripper sludge blanket depth = 4.6 m (15 ft).
- Elutriation flow = 50 to 100 percent of the stripper feed by one of the three sources:
  - Stripper underflow sludge recycle elutriation.
  - Primary effluent elutriation.
  - Reactor-clarifier overflow elutriation.
- Stripper underflow recycle to aeration basin = 0.1 to 0.2 Q.

- Stripper supernatant to reactor-clarifier = 0.1 to 0.2 Q.
- Reactor-clarifier overflow rate = 49 $m^3/m^2/d$ (1,200 gpd/sq ft).
- Reactor-clarifier pH = 9.
- Lime dosage = 100 to 300 mg/L, depending on alkalinity concentration in stripper supernatant.

A/O Process

Air Products (17) has developed a bio-kinetic simulation model that can predict the soluble phosphorus and BOD removal performance of a treatment plant under a given set of conditions. This model has been tested using the Largo A/O pilot-plant and full-scale plant data with good correlation.

Typical design parameters for the two A/O systems (33) are as follows:

Parameter	BOD and P removal	BOD, P, and N removal
Detention time, hrs		
Anaerobic stage	0.5-1.0	0.5-1.0
Anoxic stage	---	0.5-1.0
Oxic stage	1-3	3.5-6
F/M,		
kg BOD_5/day/kg MLVSS	0.2-0.6	0.15-0.25
(lbs BOD_5/day/lb MLVSS)	(0.2-0.6)	(0.15-0.25)
MLVSS, mg/L	2,000-4,000	3,000-5,000
Oxygen usage,		
kg O_2/kg BOD_5 removed	1.0	1.2
(lbs O_2/lb BOD_5 removed)	(1.0)	(1.2)
Return sludge flow, % of influent Q	10-30	20-50
Underflow concentration, % solids	2-4	1.5-3.0
Internal recycle, % of influent Q	---	100-300

Parameter	BOD and P removal	BOD, P, and N removal
Minimum D.O. (oxic stage), mg/L	2.0	2.0
Sludge wasted, kg/kg BOD_5 removed (lbs/lb BOD_5 removed)	0.5-0.8 (0.5-0.8)	0.3-0.6 (0.3-0.6)
Mixing energy (anaerobic), kw/1,000 m^3 (hp/1,000 gal)	10 (0.05)	10 (0.05)
Temperature, °C	5-30	5-30

Normally suggested formats for baffled staging of the A/O system are three anaerobic stages, three anoxic stages, and four oxic (aerobic) stages. The anoxic stages and the internal recycle are used only if nitrogen removal (i.e., nitrification/denitrification) is required. The anerobic and anoxic zones are provided with mixers and covers to avoid exposure to the atmosphere. The size of the oxic stage depends on nitrification requirements. Without oxidation of nitrogen, a hydraulic detention time of 2 to 2.5 hours is recommended. With nitrification, the oxic stages must be enlarged to 3.5 to 6 hours, depending on nitrification rate and temperature. The final clarifiers are normally designed at an overflow rate of 24.5 $m^3/m^2/d$ (600 gpd/sq ft), with a desired sludge blanket depth of below 0.6 m (2 ft). Attention should be paid to possible phosphorus bleedback within the sludge blanket due to anaerobic conditions. Use of a hydraulic bottom sweep to rapidly remove the sludge can help to mitigate phosphorus bleedback in this area. Maximum design return sludge recycle is 50 to 75 percent of influent flow.

Bardenpho Process

The Bardenpho process design approach must evaluate design requirements for each of the five stages to accomplish phosphorus removal, nitrification, and denitrification. The detention time in each of the five stages is affected by BOD_5 and total nitrogen concentration, wastewater temperature, effluent requirements, and sludge handling considerations. Typical design detention times, based on influent flow, for the five stages, are as follows:

Stage	Detention time, hours 11 plants in South Africa (Reference 44) Range	 Avg.	 Palmetto, Florida (Reference 38) Design	 Actual	 Kelowna, Canada (Reference 1) Design
Anaerobic	0.6- 1.9	1.3	1.0	1.4	2
First Anoxic	2.2- 5.2	3.2	2.7	3.8	4
Aeration (Nitrification)	6.7-19.0	11.2	4.7	6.6	9
Second Anoxic	2.2- 5.7	3.3	2.2	3.0	4
Reaeration	0.5- 1.6	1.1	1.0	1.4	2
Total	12.2-33.4	20.1	11.6	16.2	21

Sludge disposal considerations may affect the process design sizing. For example, many Bardenpho system designs, which are based on achieving nitrification and denitrification, may result in a final SRT that may be within the range of sludge stabilization by aerobic digestion. In such cases, design SRT values are increased by increasing the detention times of the aeration tanks to achieve a stable sludge in addition to nitrogen, BOD, phosphorus, and suspended solids removal (1).

The first step in the Bardenpho design is to review the factors that will determine the amount of biological phosphorus removal. Phosphorus removal will therefore depend on the amount of sludge wasted and the percent phosphorus content of the sludge. The influent BOD_5 concentration and system SRT will determine sludge production. The percent phosphorus in the waste sludge may be affected by the anaerobic zone detention time, as well as the influent soluble BOD_5 concentration. The amount of nitrate or dissolved oxygen in the recycle streams to the anaerobic zone must be minimal for effective phosphorus removal. The sludge wasting techniques must also be evaluated to maximize phosphorus removal from the system. Sludge processing and wasting techniques that result in leaching of phosphorus from the biological cells, and the subsequent return of this leached phosphorus to the Bardenpho system, will reduce phosphorus removal efficiency. Bardenpho sludges have been wasted to drying beds, applied on land, or thickened by dissolved air flotation prior to dewatering to minimize phosphorus release (1).

The first anoxic design follows a nitrogen balance performed for the system. This balance determines the amount of nitrogen oxidized by subtracting from the influent nitrogen, the nitrogen used for cell synthesis and the ammonium nitrogen in the effluent. Using a four to one internal recycle rate, two-thirds of the ammonium nitrogen oxidized in the nitrification stage is then directed to the first anoxic stage. The first anoxic stage is designed for complete denitrification of the recycled nitrate, and its volume is a function of the MLSS concentration and specific denitrification rate (64).

The remaining nitrate is denitrified in the second anoxic stage. The specific denitrification rate (64) has been described for this stage as a function of the endogenous respiration rate of the mixed liquor. This will be a function of the system SRT, temperature, and active fraction of the mixed liquor suspended solids. The volume for the second anoxic stage is then determined by the amount of nitrate that must be reduced, the specific denitrification rate, and the system MLSS concentration.

The first step in the nitrification stage design is the selection of the necessary nitrification SRT as a function of wastewater temperature. A minimal nitrification SRT predicted by Knowles (65) may be used with a 2 or 3 safety factor multiplier depending on peak to average flow conditions expected. The nitrification stage SRT is then determined using the following equation:

$$SRT_n = \frac{(MLSS)\ V_n}{Y_n\ (\Delta BOD)\,Q}$$

where:

SRT_n = Nitrification stage design SRT, day.

MLSS = Mixed liquor suspended solids, mg/L.

V_n = Nitrification stage volume, m^3 (million gallons).

Y_n = Net system sludge yield based on overall system SRT, kg SS/kg BOD_5 removed (lbs SS/lb BOD_5 removed).

ΔBOD = BOD removal in system, mg/L.

Q = Wastewater flow, m^3/d (mgd).

The total system SRT is based on all of the stages where biological growth can occur, and not just the nitrification stage. The net sludge yield includes cell synthesis and endogenous decay.

Oxygen requirements for the nitrification aeration stage are based on the amount of BOD removed, the net kg O_2/kg BOD_5 removed (lbs O_2/lb BOD_5 removed) based on the total system SRT, and the oxygen required to oxidize the ammonium nitrogen minus a credit for the equivalent oxygen available during nitrate reduction. The reaeration stage is designed both to strip enmeshed nitrogen gas bubbles from the floc matrix and to raise the mixed liquor dissolved oxygen concentration to at least 2 mg/L or higher as determined by effluent requirements.

The above design approach may involve iterations until the desired overall system SRT is met with regard to sludge aerobic stabilization needs. If the sludge is to be stabilized by additional steps or handled in a different manner, then the volume of the stages will be determined only by nitrification and denitrification needs (1).

The anaerobic contact detention time is presently based on experience. The importance of sufficient carbon for the removal of nitrates has been stressed by Barnard (45). It would appear that at a COD:TKN ratio of above 10, there are no problems in reducing the nitrates and inducing the removal of phosphorus. Primary sedimentation could change this ratio, and the degree of such removal must be determined. When there is sufficient carbon, some form of high rate primary sedimentation may be economical, and this has been applied in some plants. On the other hand, if the wastewater is weak and there is insufficient carbon to induce anaerobic conditions, provisions should be made to bypass the primary clarifier and to pass only part of the return sludge to the anaerobic zone, while bypassing the remainder to the anoxic zone. Provision of flow equalization ahead of the system can also serve to avoid the short detention time in the anaerobic contact zone during peak hydraulic flow.

OPERATIONS AND MAINTENANCE CONSIDERATIONS

In general, the three proprietary processes for phosphorus removal are not appreciably different from the equivalent conventional activated sludge process with mineral addition. A number of various mechanical problems have been experienced in all three types of plants, which have caused either delay in startup or interruptions in stable operation. These problems are more related to mechanical design and selection of equipment than to the process itself. However, process problems can be induced due to mechanical problems. Therefore, higher standards of operator training and a greater theoretical knowledge of the process on the part of operators than those for conventional activated sludge plants are required. The Bardenpho process is more complicated than PhoStrip or A/O (without nitrification) from the process standpoint, since the former involves both phosphorus and nitrogen removal. The relatively highly skilled staff and large number of sample analyses required for successful operation of a biological phosphorus removal system could well be a major burden for some small plants (44).

SECTION 3

DEVELOPMENT STATUS

PHOSTRIP PROCESS

Since the concept of the PhoStrip process was devised in 1965 by Levin (5), many pilot studies and plant-scale demonstration tests had been conducted in the early 1970's to substantiate the applicability of this process under various operating conditions. In addition, over a dozen full-scale plants employing the PhoStrip process have been constructed, many of them involving retrofitting of existing facilities. Available pilot and full-scale operations data from plants employing the PhoStrip process are presented in Table 1. The results of the findings from the available pilot tests and plant-scale data are summarized below:

- The PhoStrip process is capable of producing effluent quality with total phosphorus (TP) of 1 mg/L, most of the time, without effluent filtration.
- Excursion of total phosphorus above the 1 mg/L level can happen due to high suspended solids discharged in the final clarifier effluent. Seven of the plants shown in Table 1 include the use of effluent filters to assure that the effluent TP of 1 mg/L is met.
- The PhoStrip process is applicable to a wide range of activated sludge modes and various wastewater characteristics.
- The PhoStrip process requires less chemicals and produces less sludge than conventional mainstream treatment using lime addition for phosphorus removal.

TABLE 1. PHOSTRIP PROCESS -- PILOT AND FULL-SCALE PLANT OPERATIONS DATA

Plant and location	Design flow m^3/d (mgd)	Actual flow m^3/d (mgd)	Status	Influent T-P mg/L	Influent Ortho-P mg/L	Effluent T-P mg/L	Effluent Ortho-P mg/L	References
District of Columbia	---	---	0.038 m^3/h (10 gph) pilot test in 1972	6.4	---	0.92	0.45	11
Seneca Falls, New York	3,785 (1.0)	3,400 (0.90)	Full-scale demonstration in 1973	6.3	---	0.55	---	12
Reno-Sparks, Nevada	22,700 (6.0)	21,900 (5.8)	Plant-scale test in 1974-1975	7.7	---	1.0	---	23, 24
	---	---	1.07 m^3/h (4.7 gpm), Phase II pilot-plant test in 1976	8.4	---	---	0.8	24
	113,600 (30.0)	89,300 (23.6)	Started up in 1981; mechanical problems	8.3	---	0.75	---	25
Texas City, Texas	---	---	0.038 m^3/h (10 gph) pilot-plant test in 1976	7.9	---	0.7	---	24
Brockton, Massachusetts	---	---	1.04 m^3/h (4.6 gpm) pilot-plant test in 1976	8.7	---	1.0	---	26
	18,900 (5.0)	--- ---	Plant under construction	---	---	*	---	31
Union Carbide's Laboratory, Tonawanda, New York	---	---	0.064 m^3/h (0.28 gpm) pilot test in 1976	12	---	0.75	0.4	27
Adrian, Michigan	26,500 (7.0)	21,000 (5.6)	Started up in 1981; temporary shutdown after 5 months good operation to replace stripper feed pumps	4.5	---	0.5*	---	13, 31
Central Contra Costa Sanitary District, Walnut Creek, California	---	---	0.45 m^3/h (2 gpm) pilot-plant operation in 1981; Phase Id data	10	---	1.0	0.2	28

*Effluent filters used.

TABLE 1. (continued)

Plant and location	Design flow m^3/d (mgd)	Actual flow m^3/d (mgd)	Status	Influent T-P mg/L	Influent Ortho-P mg/L	Effluent T-P mg/L	Effluent Ortho-P mg/L	References
Amherst, New York	90,800 (24.0)	79,100 (20.9)	Started up in 1982; mechanical problems; PhoStrip process discontinued in February 1983 due to severe scaling in lime feed piping	4.3	---	0.8*	---	29, 30
Carpentersville, Illinois	18,900 (5.0)	--- ---	Worked well; shut down after one year when state stopped phosphorus removal enforcement	---	---	---	---	1, 13
Lansdale, Pennsylvania	9,500 (2.5)	--- ---	Started up in 1982; working well	5.8	---	0.9	---	1, 19, 31
Lititz, Pennsylvania	13,200 (3.5)	--- ---	Startup delayed due to inadequate flow to plant	---	---	---	---	1, 19
Little Patuxent, Maryland (The Savage Plant)	56,800 (15.0)	--- ---	Started up in 1982; process difficulty during summer of 1983; now recovered	6-9	---	1-2*	---	1, 13
Southdowns, New York	60,600 (16.0)	--- ---	Started up in 1982	3.2	---	0.5*	---	31
Texas City, Texas	30,300 (8.0)	--- ---	Mechanical problems; PhoStrip not in operation	---	---	*	---	1, 19
Ithaca, New York	37,800 (10.0)	--- ---	Under construction	---	---	---	---	31
Rochester, New York	71,900 (19.0)	--- ---	Under construction	---	---	---	---	31
Tahoe/Truckee, Nevada	18,900 (5.0)	--- ---	Under construction	---	---	*	---	31

*Effluent filters used.

The PhoStrip process was marketed by Biospherics, Inc. until 1974 when Union Carbide purchased the Levin patent. Biospherics reacquired the PhoStrip rights in 1981, and is presently marketing the process at the following address:

Biospherics Incorporated
4928 Wyaconda Road
Rockville, Maryland 20852

Telephone: 301-770-7700

The equipment used in the PhoStrip process includes concrete or steel tanks, mixers, pumps, and lime feed facilities. These are all conventional wastewater treatment facilities and are available from many competitive equipment suppliers. However, there have been many cases of mechanical difficulties observed during startup. There is need to provide a more reliable equipment package, particularly those related to transfer pumps, lime handling facilities, and automatic control instrumentation.

A/O PROCESS

Since the A/O process was developed and patented by Air Products and Chemicals, Inc. in the 1970's, a number of laboratory-scale and pilot-plant tests have been conducted, including those at Bath, Pennsylvania; Washington, DC; Allentown, Pennsylvania; Rochester, New York; and Largo, Florida. The only plant-scale demonstration facility existing so far is the 3.0-mgd retrofitted portion of the plant at Largo, Florida. After completing pilot and plant-scale A/O studies, the City of Largo decided to expand their entire 9-mgd plant to 15 mgd. Full-scale A/O plants for several municipalities are currently in the design stage or under construction. Available data from pilot and plant-scale operations employing the A/O process are presented in Table 2. The results of findings from the pilot and plant-scale tests are summarized as follows:

- Soluble ortho-phosphorus can be reduced to less than 1 mg/L by the A/O system without nitrification in a relatively short detention time (less than 4 hours).

- Data from the Largo demonstration plant showed that the A/O system with nitrification produced effluent soluble phosphorus in excess of 1 mg/L during the first four months, but less than 1 mg/L after that period of acclimation. Ammonia nitrogen was generally reduced to less than 2 mg/L, which indicated that nitrification was quite effective. However, nitrate and nitrite levels in the treated

TABLE 2. A/O PROCESS -- PILOT AND FULL-SCALE PLANT OPERATIONS DATA

Plant and location	Design flow m^3/d (mgd)	Actual flow m^3/d (mgd)	Status	Influent T-P mg/L	Influent Ortho-P mg/L	Effluent T-P mg/L	Effluent Ortho-P mg/L	References
Bath, Pennsylvania	---	---	11-21 liters (3-5.5 gal) bench-scale laboratory tests; A/O without nitrification (2.6 hours detention)	20.	---	---	4.4	17
Washington, DC	---	---	Pilot-plant data	---	3.4	---	0.1	31
Allentown, Pennsylvania	---	---	Pilot-plant data; A/O without nitrification (3.7 hours detention)	18.	---	---	0.3	32
Rochester, New York	---	---	2.8 m^3 (750 gal) pilot plant; A/O without nitrification (2.0 hours detention)	---	2.23	---	0.49	16, 17
			A/O with nitrification (4.0 hours detention)	---	4.1	---	0.38	16, 17
Largo, Florida	---	---	2.8 m^3 (750 gal) pilot plant; A/O without nitrification (2.1 hours detention)	---	5.83	---	1.03	17
	11,400 (3.0)	12,100 (3.2)	Demonstration plant; A/O with nitrification (4.2 hours detention); March 1980 performance test data	8.9	---	1.85	0.51	17, 34, 35
			City operation; A/O without nitrification; February-June 1981 data	---	---	1.35	0.64	17
			City operation; A/O with nitrification; July 1981 - February 1982 data	---	---	1.77	1.04	17

TABLE 2. (continued)

Plant and location	Design flow m^3/d (mgd)	Actual flow m^3/d (mgd)	Status	Influent		Effluent		References
				T-P mg/L	Ortho-P mg/L	T-P mg/L	Ortho-P mg/L	
Largo, Florida (continued)	56,800 (15.0)	--- ---	Plant expansion under construction	---	---	---	---	17, 36
Patapsco Plant, Baltimore, Maryland	---	---	Pilot-plant in progress	---	---	---	---	36
	265,000 (70.0)	--- ---	Retrofit selected but not yet in design	---	---	---	---	
Lancaster, Pennsylvania	34,000 (9.0)	--- ---	Retrofit in design	---	---	---	---	36
	79,500 (21.0)	--- ---	Plant in design	---	---	---	---	
Huron, Michigan	90,800 (24.0)	--- ---	Plant in design	---	---	---	---	36
Springettsbury, Pennsylvania	56,800 (15.0)	--- ---	Plant in design	---	---	---	---	36
Liberty Lake, Washington	7,600 (2.0)	--- ---	Plant in design	---	---	---	---	36
Cox Creek, Maryland	56,800 (15.0)	--- ---	Retrofit selected but not yet in design	---	---	---	---	36
Titusville, Florida	22,700 (6.0)	--- ---	Selected but not yet in design	---	---	---	---	36

effluent were in the range of 8 to 10 mg/L, which indicated that only partial denitrification was attained. The ability of the A/O system to achieve a high degree of denitrification and to produce effluent soluble phosphorus of less than 1 mg/L on a consistent basis remains to be demonstrated.

- The performance of the A/O system is dependent on the ratio of soluble BOD to phosphorus in the feed to the system; it will operate best when the ratio is greater than approximately 10 to 1.
- Phosphorus removal performance remained relatively stable as operating temperature was decreased from 15°C to 10°C, and actually improved as operating temperature was further decreased from 10°C to 5°C.
- The A/O system produces a phosphorus-rich (4.2 to 6 percent by weight) excess sludge which must be further stabilized before final disposal.
- Concentrations of total phosphorus (i.e., soluble plus suspended form) in the A/O effluent at Largo were in the range of 1.3 to 2.0 mg/L. The phosphorus concentrations were attributable to the total suspended solids (TSS) in the clarifier effluent. (For example, if the TSS were 20 mg/L in the clarifier effluent and contained 5 percent of P, the phosphorus in these solids would amount to 1.0 mg/L). Therefore, effluent filters will be necessary if effluent limitations call for total phosphorus not to exceed 1 mg/L.
- Chemical treatment may be required to reduce the amounts of phosphorus contained in the internal sidestreams, particularly in the case of supernatants from anaerobic digesters.

Additional information on A/O can be obtained from the following address:

Environmental Products Department
Air Products and Chemicals, Inc.
Box 538
Allentown, Pennsylvania 18105

Telephone: 215-481-4911

The equipment used in the A/O process includes concrete or steel tanks, mixers, aerators, clarifiers, and pumps for recycle and sludge handling. As in the case of the PhoStrip process, these are all conventional facilities available from many equipment suppliers.

BARDENPHO PROCESS

The original process developed by Barnard (14) in the early 1970's was a single-sludge, four-stage (anoxic-aeration-anoxic-reaeration) system intended for nitrogen removal by biological nitrification and denitrification. The modified Bardenpho process is a five-stage system, with an anaerobic stage added ahead of the original four-stage system for biological phosphorus removal (see Figure 3). Over 30 wastewater treatment plants employing the Bardenpho process for both phosphorus and nitrogen removal have been designed or operated in South Africa (44). The first facility employing this process in the U.S. is the 5,300 m^3/d (1.4 mgd) plant located in Palmetto, Florida. Another Bardenpho system, the 3,200 m^3/d (0.85 mgd) plant in Pluckemin, New Jersey, started operation in late 1982. The first Bardenpho system in Canada is the 60,600 m^3/d (6 mgd) facility in Kelowna, British Columbia, which started operation in mid-1982. Available pilot and full-scale operations data from plants employing the Bardenpho process are presented in Table 3. The results of findings from the pilot and plant-scale tests are summarized as follows:

- Bardenpho is a promising process for removal of both phosphorus and nitrogen, although limited operating data from the existing plants show inconsistencies in plant performance.

- Many plants in South Africa produce variable concentrations of effluent phosphorus (see Table 3), possibly due to a combination of reasons, such as weak wastewater strength in the feed, high TKN-to-carbon ratio, and low plant flow relative to design capacity.

- The capability of the process to consistently produce total phosphorus of less than 2 mg/L, or ortho-phosphate of less than 1 mg/L as P, remains to be demonstrated. At Palmetto, Florida, the average total phosphorus concentration during the period between April and September 1980 was 2.2 mg/L after effluent filters. Addition of a small dose of alum was necessary to reduce the total phosphorus to 0.8 mg/L (1).

TABLE 3. BARDENPHO PROCESS -- PILOT AND FULL-SCALE PLANT OPERATIONS DATA

Plant and location	Design flow m^3/d (mgd)	Actual flow m^3/d (mgd)	Status	Influent		Effluent		References
				T-P mg/L	Ortho-P mg/L	T-P mg/L	Ortho-P mg/L	
Palmetto, Florida	5,300 (1.4)	4,600 (1.22)	Design detention = 11.6 hours; started up in October 1979; February-April 1980 operating data	8.2	---	2.5*	---	37, 38, 39
		4,100 (1.08)	April-September 1980 operating data	6.2	---	2.2*	---	1
		3,785 (1.00)	October 1981-March 1982 operating data (with minimal alum dosage added)	7.6	---	0.8*	---	1
Kelowna, B.C., Canada	60,600 (6.0)	--- ---	Design detention = 21 hours; started up in July 1982; first 6 weeks of operating data	---	---	---	0.2*	1
Pluckemin, New Jersey	3,200 (0.85)	--- ---	Started up in late 1982	---	---	---	---	1
Daspoort, Pretoria, South Africa	---	---	4.1 m^3/h (18 gpm) pilot plant	10.5 10.	--- ---	1.0** 1.5	--- ---	15, 40 41
Alexandra Plant, Johannesburg, South Africa	---	---	Full-scale plant modifications operating data	6.7	---	0.3**	---	15, 42, 43
Olifantsvlei Plant, Johannesburg, South Africa	---	---	Full-scale plant modifications operating data	4.2	---	2.2**	---	15, 42, 43
Johannesburg, South Africa	---	---	Laboratory-scale plant No. 1	9	---	<1	---	41
Goukoppies, South Africa	---	---	Laboratory-scale plant No. 1 (MLSS = 2,700 mg/L)	6.6	---	1.7	---	41
	---	---	Laboratory-scale plant No. 2 (MLSS = 3,100 mg/L)	6.6	---	1.1	---	41
Northern Works, South Africa	---	---	Laboratory-scale plant No. 1 (MLSS = 1,300 mg/L)	7.1	---	---	6.4	41

*Effluent filters used.
**Not specified as either total or ortho-phosphorus.

TABLE 3. (continued)

Plant and location	Design flow m^3/d (mgd)	Actual flow m^3/d (mgd)	Status	Influent		Effluent		References
				T-P mg/L	Ortho-P mg/L	T-P mg/L	Ortho-P mg/L	
Northern Works, South Africa (continued)	---	---	Laboratory-scale plant No. 2 (MLSS = 2000 mg/L; primary sludge added to system)	10.	---	---	<1	41
Secunda, South Africa	3,400 (0.9)	4,900 (1.3)	Started up in October 1976 (toxic and aerobic zones not physically separated)	---	3-10	---	1	1, 44
Roodepoort, South Africa	6,800 (1.8)	4,200 (1.1)	Started up in March 1978	13	---	9	---	1, 44
Vanderbijlpark, South Africa	9,100 (2.4)	--- ---	Started up in October 1979	---	2-7	---	2-7	1, 44
Meyertown, South Africa	4,900 (1.3)	3,000 (0.8)	Started up in April 1977	9	---	---	1-7	1, 44
Standerton, South Africa	4,500 (1.2)	3,000 (0.8)	Started up in June 1979	---	15	---	6-10	1, 44
Benoni, South Africa	7,600 (2.0)	4,500 (1.2)	Started up in August 1979	10	---	7	---	1, 44
Klerksdorp, South Africa	7,900 (2.1)	15,900 (4.2)	Started up in February 1979 (no secondary anoxic stage)	---	---	1**	---	1, 44
Stilfontein, South Africa	10,600 (2.8)	5,300 (1.4)	Started up in March 1977	---	---	---	---	1, 44
Baviannpoort, South Africa	15,900 (4.2)	9,500 (2.5)	Started up in August 1979; poor phosphorus removal due to high TKN/carbon ratio	---	15	---	11	1, 44, 45
Northern Works, Johannesburg, South Africa	151,400 (40.0)	75,700 (20.0)	Design detention = 14 hours; started up in November 1979; low strength of feed from primary effluent caused poor phosphorus removal	9.4	---	7.1	6.0	1, 44, 46

*Effluent filters used.
**Not specified as either total or ortho-phosphorus.

TABLE 3. (continued)

Plant and location	Design flow m^3/d (mgd)	Actual flow m^3/d (mgd)	Status	Influent		Effluent		References
				T-P mg/L	Ortho-P mg/L	T-P mg/L	Ortho-P mg/L	
		37,100 (9.8)	Primary sludge added to system during an experimental period to increase feed strength and improve performance; experiment terminated to correct problems related to rag	10	4.0	1.3	1.3	46
Goudkoppies Plant, Johannesburg, South Africa	151,400 (40.0)	98,400 (26.0)	Design detention = 14 hours; started up in December 1977; 1980-1981 operating data	7.5	---	1.4	0.7	1, 44, 46
Randfontain, South Africa	9,800 (2.6)	--- ---	---	---	---	---	---	1
Indhoek, South Africa	11,000 (2.9)	--- ---	---	---	---	---	---	1
Cape Flats, South Africa	151,400 (40.0)	--- ---	---	---	---	---	---	1
Mitchell's Plain, South Africa	22,000 (5.8)	--- ---	---	---	---	---	---	1
Witbank, South Africa	22,000 (5.8)	--- ---	---	---	---	---	---	1
Potchefstroom, South Africa	9,800 (2.6)	--- ---	---	---	---	---	---	1
Que Que, Zimbabwe	9,800 (2.6)	--- ---	---	---	---	---	---	1
Umtall, Zimbabwe	9,800 (2.6)	--- ---	---	---	---	---	---	1
Salisbury, Zimbabwe	36,300 (9.6)	--- ---	---	---	---	---	---	1
Bulawayo, Zimbabwe	9,800 (2.6)	--- ---	---	---	---	---	---	1

*Effluent filters used.
**Not specified as either total or ortho-phosphorus.

- At the Palmetto plant, the polishing filters remove only 3 to 4 mg/L of suspended solids. The suspended solids concentrations in the clarifier effluent are very low (average of less than 5 mg/L) before final filtration treatment, due to the very low sludge volume index (SVI) and rapid sludge settling characteristics. This plant maintains a solids residence time (SRT) of approximately 20 days, which is in the low range of 20 to 40 days typically found in the Bardenpho process.

- Problems encountered during the start-up period at the Palmetto facility were related to the internal recycle pumps. Without the internal recycle, effluent nitrate concentrations exceeded 8 to 10 mg/L, which caused biological phosphorus removal to decrease markedly to less than 50 percent. This was actually a mechanical problem rather than one related to the process itself. Once the recycle pumps were operable, the effluent nitrate concentration decreased and phosphorus removal improved.

The Bardenpho process is marketed in the United States by Envirotech at the following address:

EIMCO Process Machinery Division
Envirotech Corporation
669 West Second South
P.O. Box 300
Salt Lake City, Utah 84110

Telephone: 801-526-2000

As in the case of the PhoStrip and A/O processes, the equipment used in the Bardenpho process includes the conventional facilities of concrete or steel tanks, mixers, aerators, clarifiers, and pumps.

SECTION 4

COMPARISON WITH EQUIVALENT TECHNOLOGIES

EQUIVALENT CONVENTIONAL CONCEPT

Although the primary purpose of this evaluation is to compare the costs for phosphorus removal, the PhoStrip, A/O, and Bardenpho processes have different levels of applications with respect to their capability to provide various degrees of BOD, phosphorus, and nitrogen removal. Due to this complexity, these three processes should not be compared with each other indiscriminately. The conventionally-available phosphorus removal methods primarily involve mineral addition with alum, ferric chloride, or pickle liquor.

The total costs involved for using ferric chloride are slightly less than those for alum; however, iron and color concentrations in plant effluents treated with ferric chloride or pickle liquor may become a concern on occasion. The costs involved in using two-stage tertiary lime treatment are usually higher than those for alum treatment, except in the case of very large plants (see Reference 66, Fact Sheets 4.2.2 vs 5.1.1). Furthermore, lime treatment generates more solids handling, as well as potential precipitation and line freezing problems. For all of the above considerations, the conventional activated sludge treatment (one, two, or three separate-stage systems, depending on the degree of nitrogen removal involved), together with alum addition, is assumed as the baseline technology for cost comparison with the three proprietary phosphorus removal processes. The alternative cases evaluated for costs and energy requirements in this technology assessment report are depicted in Table 4. The alternative cases included here are considered to be among those more frequently encountered, but are not meant to be exhaustive.

It should be further noted that, in this model comparison, it was assumed the PhoStrip process could produce effluent TP of 1 mg/L, and that the A/O and Bardenpho processes could produce effluent TP of 2 mg/L without effluent filters.

TABLE 4. ALTERNATIVE CASES EVALUATED UNDER TECHNOLOGY ASSESSMENT OF BIOLOGICAL PHOSPHORUS REMOVAL

Alternative cases	A (Baseline) Activated sludge with alum addition			B	C	D
	1-Stage	2-Stage	3-Stage	PhoStrip	A/O	Bardenpho
1. Phosphorus removal (effluent TP = 1 mg/L)	1-A			1-B	1-C	
2. Phosphorus removal (effluent TP = 2 mg/L)	2-A			2-B	2-C	
3. Phosphorus removal and nitrification (effluent TP = 2 mg/L, NH_3-N = 1 mg/L)		3-A			3-C (*)	
4. Phosphorus removal and nitrification/ denitrification (effluent TP = 2 mg/L, TN = 3 mg/L)			4-A			4-D

TP = Total phosphorus.
TN = Total nitrogen.
* = Partial denitrification to TN = 10 mg/L in A/O process per Largo, Florida data.

The related sludge handling processes assumed in the model are as follows:

- Thickening of waste activated sludge by Dissolved Air Flotation (DAF) for all plant sizes except 1,892 m^3/d (0.5 mgd).
- Stabilization of primary and waste activated sludge (except the latter from Bardenpho) by aerobic digestion for plants smaller than 37,850 m^3/d (10 mgd), or anaerobic digestion for plants greater than 37,850 m^3/d (10 mgd).
- Dewatering of stabilized sludge by sludge drying bed for plants smaller than 3,785 m^3/d (1 mgd), or vacuum filtration for plants greater than 3,785 m^3/d (1 mgd).
- Sludge hauling (32 km (10 miles) one way) and landfilling for all plant sizes.

COST COMPARISON

For each of the alternatives indicated in Table 4, costs were developed for three plant sizes based on average design flow:

1. 1,892 m^3/d (0.5 mgd)
2. 18,925 m^3/d (5.0 mgd)
3. 189,250 m^3/d (50.0 mgd)

In each case, costs were compared on a "total plant" basis since the various processes would generate different amounts of biological and inorganic solids, which affect sludge handling and disposal costs.

The economic analysis of the three proprietary processes and baseline technologies considered the initial investment cost (capital cost), the annual operation and maintenance cost, and the present worth cost of the total treatment system. Cost estimates developed by the U.S. EPA for evaluating innovative and alternative technologies (66) were used as the primary source for estimating installed capital, and annual operation and maintenance costs for most of the unit processes involved. These cost estimates were supplemented with cost figures from Appendix H of the Areawide Assessment Procedures Manual (67) for the nonstructural cost components (e.g., influent pumping or lift station, and miscellaneous structures such as control buildings, outfall sewer, etc.). Cost curves for the A/O and Bardenpho processes were not available in the literature; therefore, these costs were developed by WESTON based on preliminary concept design of the facilities and in-house cost estimates.

All cost estimates were updated to reflect October 1982 construction costs (Engineering News Record Construction Cost Index 3875). The basic assumptions and procedures utilized in estimating construction costs are summarized in Appendix A.

The estimated capital, O&M, and total present worth costs for each of the alternative cases and different plant sizes are presented in Tables B-1 through B-12 in Appendix B. Tables 5, 6, 7, and 8 show the summaries of cost comparison for equivalent alternative cases. A summary of least cost alternatives (based on total present worth) is presented in Table 9. The cost curves for capital and total present worth costs for these alternatives are depicted in Figures 5(a), 6(a), 7(a), and 8(a). The cost curves for comparative O&M costs are presented in Figures 5(b), 6(b), 7(b), and 8(b).

It should be noted that site specific conditions will effect changes in the relative costs of each of these alternative technologies and, therefore, these estimates are merely presented as guidance to potential users to assist their cost-effective analyses in terms of procedure and reasonable default values. Also, no consideration has been given to retrofit applications, which greatly accentuate the controlling nature of site specific conditions.

ENERGY REQUIREMENTS

An approach similar to that utilized for cost comparison was used for estimating the energy requirements for the alternative cases shown in Table 4. The estimated energy requirements by unit processes are presented in Tables B-13 through B-24 in Appendix B, and summarized in Table 10. Those alternatives requiring the least amount of energy are also denoted in Table 10.

TABLE 5. SUMMARY OF COST COMPARISON[1]

CASE 1
PHOSPHORUS REMOVAL
(EFFLUENT TP = 1 mg/L)

Alternative	Costs	Plant size 1,892 m^3/d (0.5 mgd)	 18,925 m^3/d (5 mgd)	 189,250 m^3/d (50 mgd)
1-A (Baseline)	Capital[2], $	2,461,000	9,628,000	49,306,000
	O&M, $/year	202,000	805,000	5,200,000
	Total present worth, $	4,501,000(*)	17,757,000(*)	101,817,000
1-B	Capital[2], $	3,373,000	11,182,000	52,416,000
	O&M, $/year	253,000	690,000	3,666,000
	Total present worth, $	5,928,000	18,150,000	89,436,000(*)
1-C	Capital[2], $	2,990,000	11,763,000	56,319,000
	O&M, $/year	210,000	775,000	4,212,000
	Total present worth, $	5,111,000	19,589,000	98,853,000

Alternative 1-A = One-stage activated sludge system with alum addition.

Alternative 1-B = PhoStrip.

Alternative 1-C = A/O (4 hours total detention) with effluent filters.

---

[1] See Tables B-1, B-2, and B-3 in Appendix B for breakdown of costs by unit processes.

[2] ENR Construction Cost Index = 3875.

(*) Denotes least cost alternative.

TABLE 6. SUMMARY OF COST COMPARISON[1]

CASE 2
PHOSPHORUS REMOVAL
(EFFLUENT TP = 2 mg/L)

Alternative	Costs	Plant size		
		1,892 m^3/d (0.5 mgd)	18,925 m^3/d (5 mgd)	189,250 m^3/d (50 mgd)
2-A (Baseline)	Capital[2], $	2,451,000	9,602,000	49,113,000
	O&M, $/year	197,000	774,000	4,890,000
	Total present worth, $	4,440,000	17,418,000	98,494,000
2-B	Capital[2], $	3,373,000	11,182,000	52,416,000
	O&M, $/year	253,000	690,000	3,666,000
	Total present worth, $	5,928,000	18,150,000	89,436,000
2-C	Capital[2], $	2,496,000	9,600,000	46,419,000
	O&M, $/year	183,000	641,000	3,540,000
	Total present worth, $	4,344,000(*)	16,073,000(*)	82,167,000(*)

Alternative 2-A = One-stage activated sludge system with alum addition.

Alternative 2-B = PhoStrip.

Alternative 2-C = A/O (4 hours total detention).

---

[1] See Tables B-4, B-5, and B-6 in Appendix B for breakdown of costs by unit processes.

[2] ENR Construction Cost Index = 3875.

(*) Denotes least cost alternative.

TABLE 7. SUMMARY OF COST COMPARISON[1]

CASE 3
PHOSPHORUS REMOVAL AND NITRIFICATION
(EFFLUENT TP = 2 mg/L, NH_3-N = 1 mg/L)

Alternative	Costs	Plant size 1,892 m^3/d (0.5 mgd)	 18,925 m^3/d (5 mgd)	 189,250 m^3/d (50 mgd)
3-A (Baseline)	Capital[2], $	2,990,000	11,376,000	56,239,000
	O&M, $/year	227,000	854,000	5,369,000
	Total present worth, $	5,282,000	20,000,000	110,457,000
3-C	Capital[2], $	2,788,000	10,596,000	52,501,000
	O&M, $/year	195,000	702,000	3,952,000
	Total present worth, $	4,757,000(*)	17,685,000(*)	92,409,000(*)

Alternative 3-A = Two-stage activated sludge system with alum addition.

Alternative 3-C = A/O (6 hours total detention) for nitrification and partial denitrification to TN = 10 mg/L.

---

[1] See Tables B-7, B-8, and B-9 in Appendix B for breakdown of costs by unit processes.

[2] ENR Construction Cost Index = 3875.

(*) Denotes least cost alternative.

TABLE 8. SUMMARY OF COST COMPARISON[1]

CASE 4
PHOSPHORUS REMOVAL AND NITRIFICATION/DENITRIFICATION
(EFFLUENT TP = 2 mg/L, TN = 3 mg/L)

Alternative	Costs	Plant size		
		1,892 m^3/d (0.5 mgd)	18,925 m^3/d (5 mgd)	189,250 m^3/d (50 mgd)
4-A (Baseline)	Capital[2], $	3,433,000	12,913,000	64,576,000
	O&M, $/year	274,000	1,112,000	7,469,000
	Total present worth, $	6,200,000	24,142,000	140,000,000
4-D	Capital[2], $	2,947,000	12,026,000	68,742,000
	O&M, $/year	190,000	701,000	4,219,000
	Total present worth, $	4,866,000(*)	19,105,000(*)	111,347,000(*)

Alternative 4-A = Three-stage activated sludge system with alum addition.

Alternative 4-D = Bardenpho (16 hours total detention).

---

[1] See Tables B-10, B-11, and B-12 in Appendix B for breakdown of costs by unit processes.

[2] ENR Construction Cost Index = 3875.

(*) Denotes least cost alternative.

TABLE 9. SUMMARY OF LEAST COST ALTERNATIVES[1]

Alternative[2]	Plant size 1,892 m^3/d (0.5 mgd)	 18,925 m^3/d (5 mgd)	 189,250 m^3/d (50 mgd)
1-A (Baseline)	(*)	(*)	---
1-B (PhoStrip)	---	---	(*)
1-C (A/O)	---	---	---
2-A (Baseline)	---	---	---
2-B (PhoStrip)	---	---	---
2-C (A/O)	(*)	(*)	(*)
3-A (Baseline)	---	---	---
3-C (A/O)	(*)	(*)	(*)
4-A (Baseline)	---	---	---
4-D (Bardenpho)	(*)	(*)	(*)

[1] Based on total present worth costs.
[2] See Table 4 for definition of alternative.

TABLE 10. SUMMARY OF ENERGY REQUIREMENTS[1] IN 10^3 KWH/YEAR

Alternative[2]	Plant size 1,892 m^3/d (0.5 mgd)	 18,925 m^3/d (5 mgd)	 189,250 m^3/d (50 mgd)
1-A (Baseline)	309(*)	3,171	21,950
1-B (PhoStrip)	353	3,146(*)	20,960(*)
1-C (A/O)	364	3,353	23,489
2-A (Baseline)	309(*)	3,171	21,950
2-B (PhoStrip)	353	3,146	20,960
2-C (A/O)	332	3,028(*)	20,389(*)
3-A (Baseline)	393(*)	3,815	27,902
3-C (A/O)	440	3,758(*)	26,453(*)
4-A (Baseline)	417	4,035	30,002(*)
4-D (Bardenpho)	383(*)	3,832(*)	32,125

[1] See Tables B-13 through B-24 in Appendix B for breakdown of energy requirements by unit processes.

[2] See Table 4 for definition of alternatives.

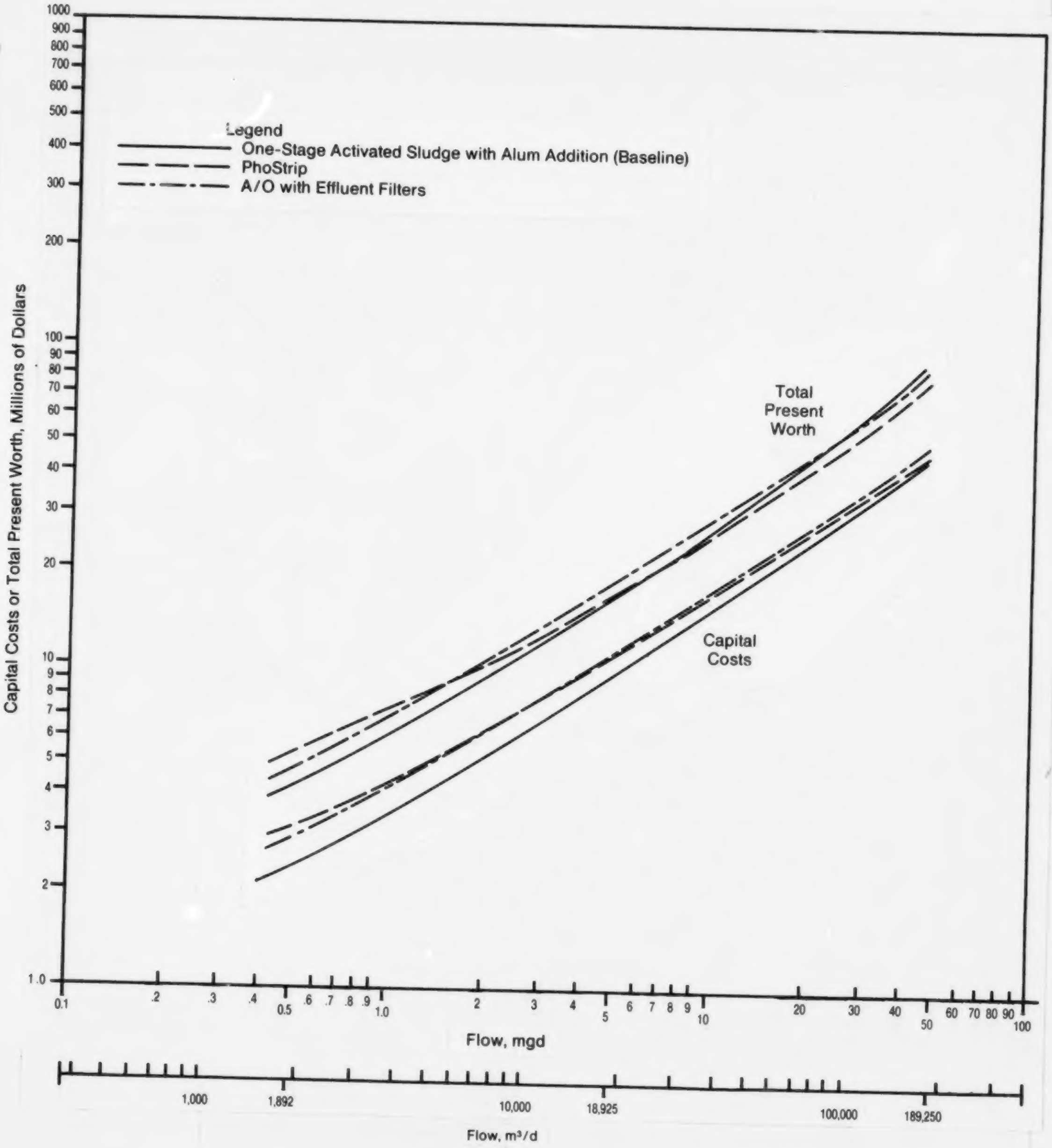

Figure 5(a). **Capital cost comparison.**
Case 1: Phosphorus removal (effluent TP = 1 mg/l).

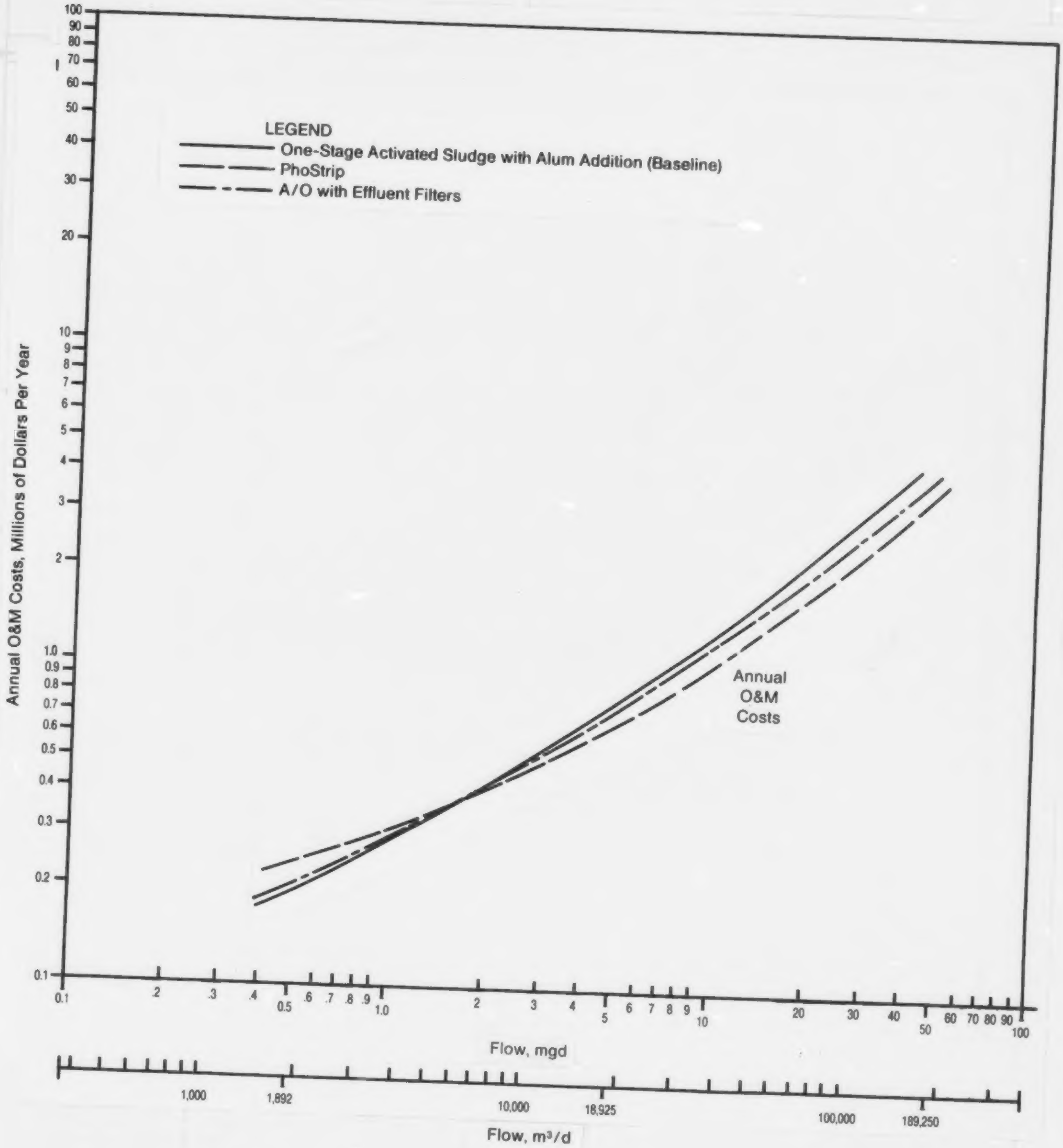

Figure 5(b). **O&M cost comparison.**
Case 1: Phosphorus removal (effluent TP = 1 mg/l).

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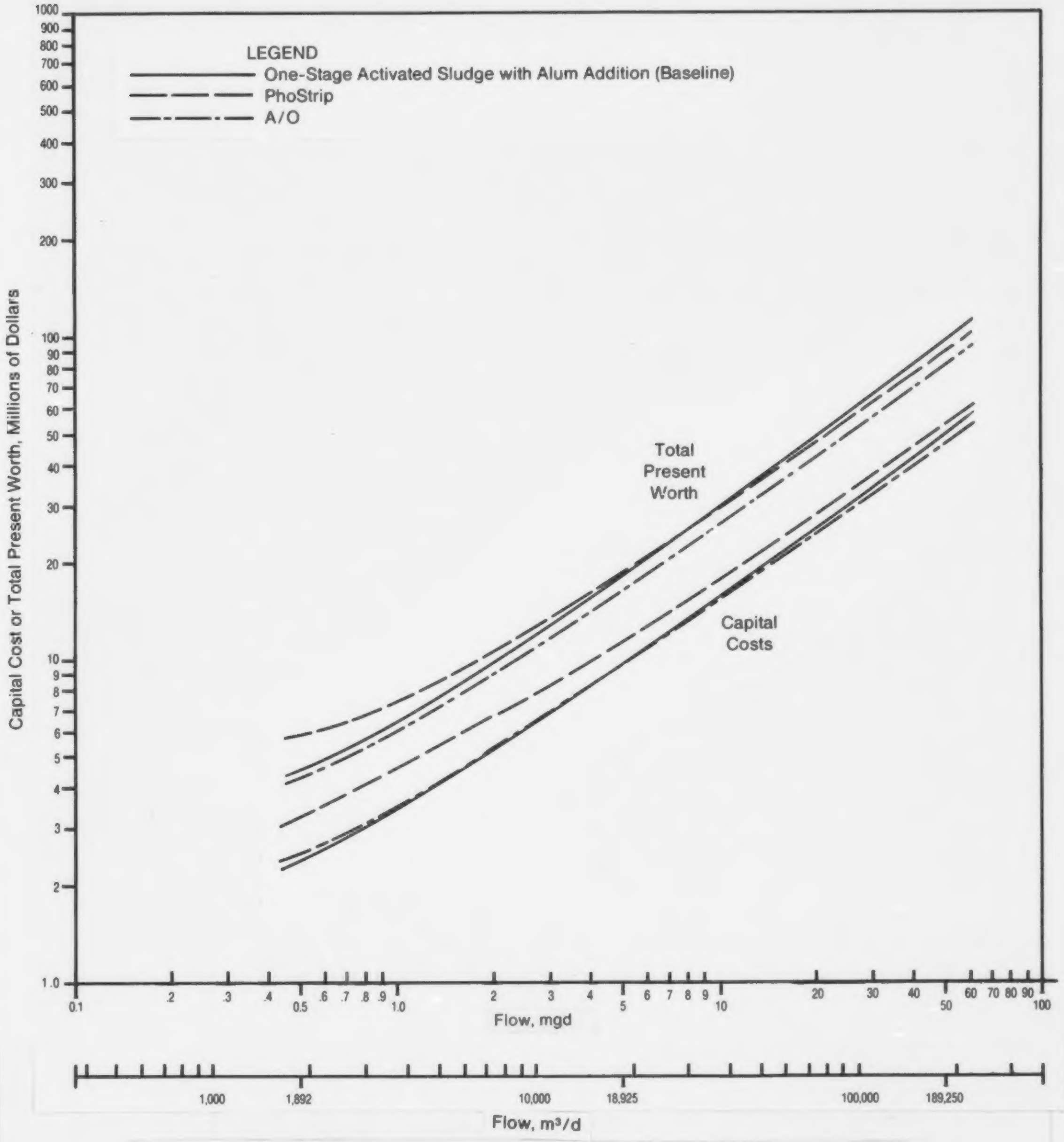

Figure 6(a). **Capital cost comparison.**
Case 2: Phosphorus removal (effluent TP = 2 mg/l).

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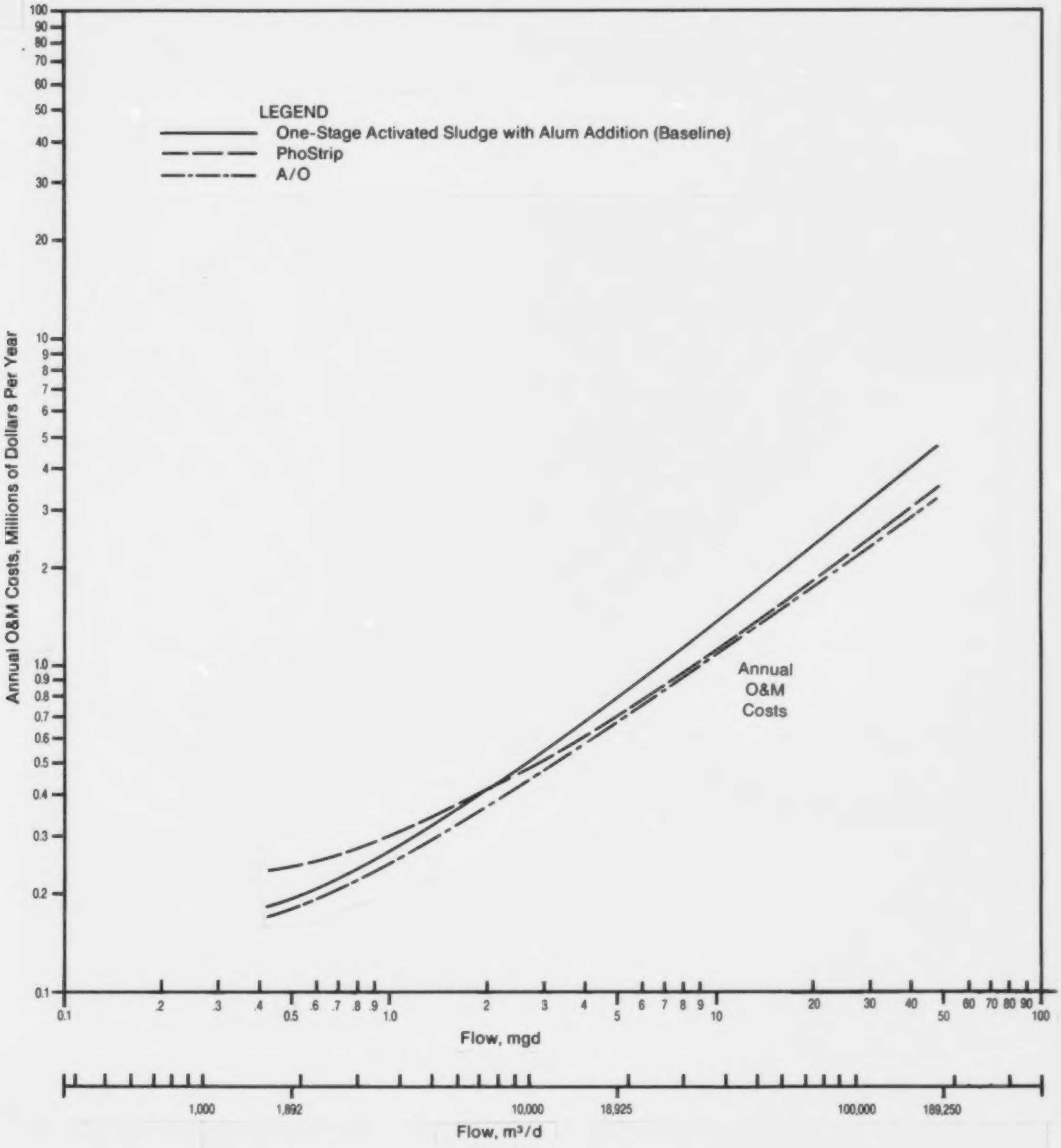

Figure 6(b). O&M cost comparison.
Case 2: Phosphorus removal (effluent TP = 2 mg/l).

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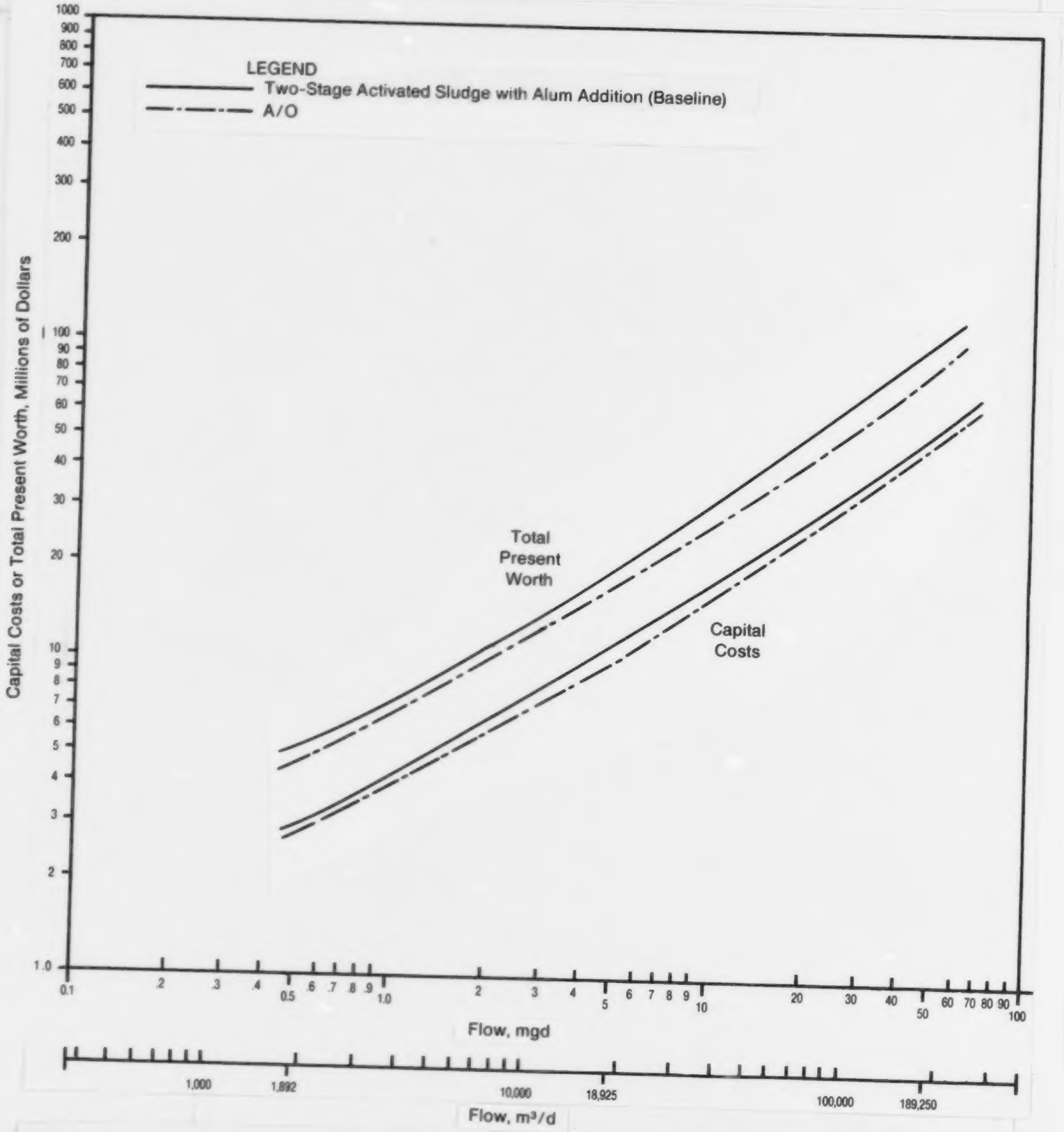

Figure 7(a). **Capital cost comparison.**
Case 3: Phosphorus removal (effluent TP = 2 mg/l, NH_3-N = 1 mg/l).

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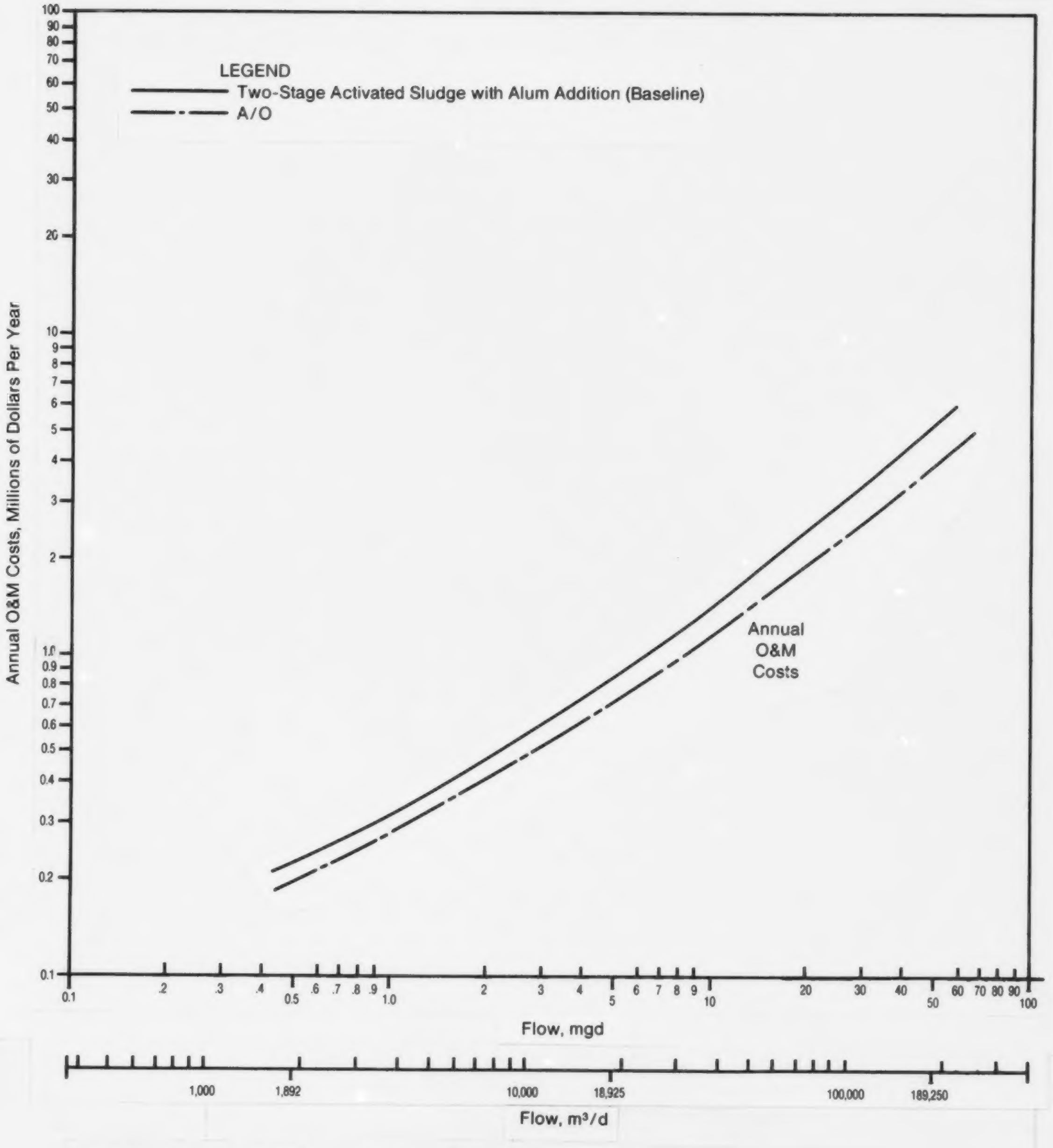

Figure 7(b). **O&M cost comparison.**
Case 3: Phosphorus removal (effluent TP = 2 mg/l, NH_3-N = 1 mg/l).

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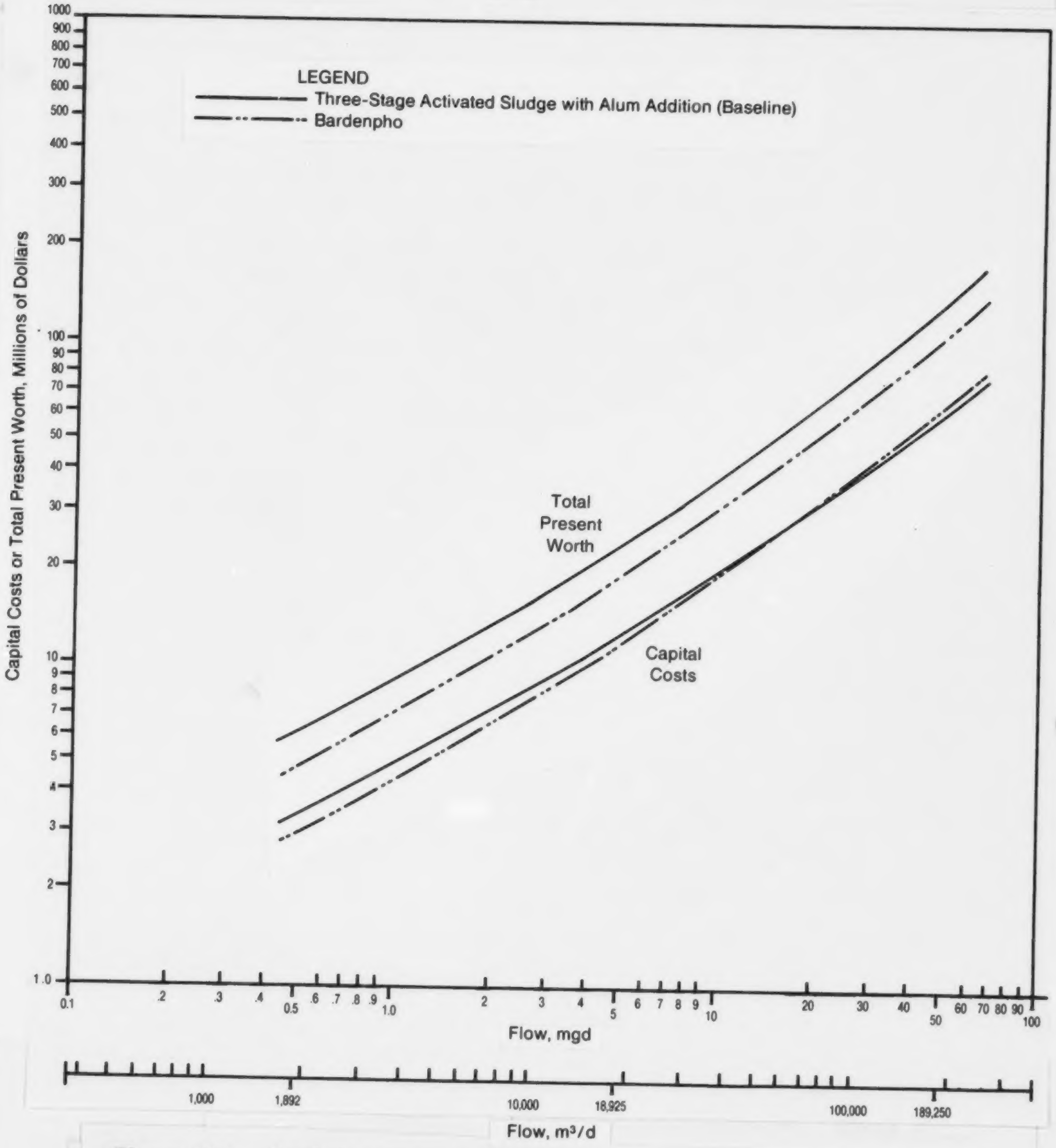

Figure 8(a). **Capital cost comparison.**
Case 4: Phosphorus removal, nitrification and denitrification (effluent TP = 2 mg/l, TN = 3 mg/l).

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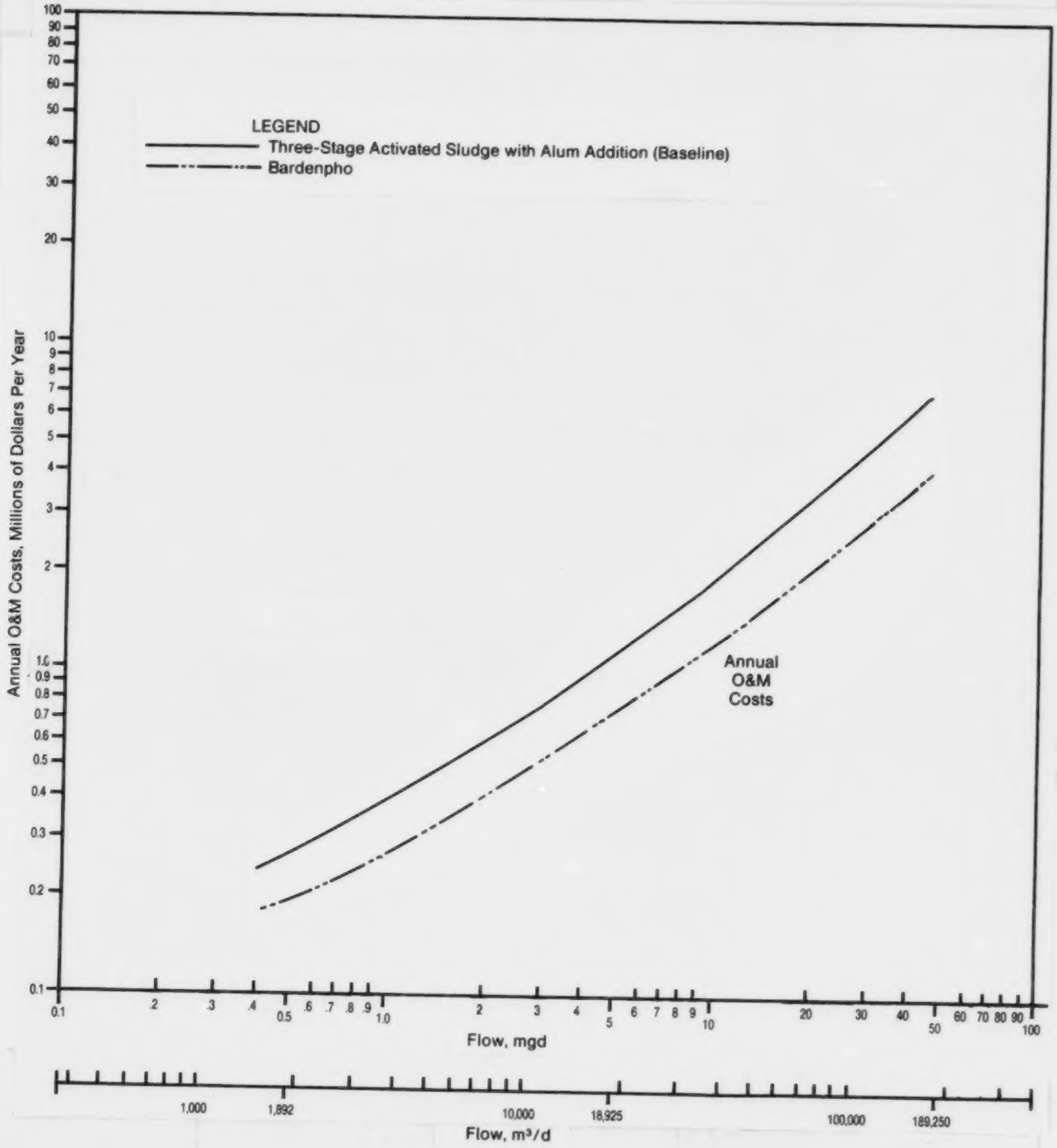

Figure 8(b). **O&M cost comparison.**
Case 4: Phosphorus removal, nitrification and denitrification (effluent TP = 2 mg/l, TN = 3 mg/l).

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SECTION 5

ASSESSMENT OF NATIONAL IMPACT

MARKET POTENTIAL

The needs for phosphorus and nitrogen removal in the United States have been projected by the U.S. EPA in the "1980 Needs Survey for Conveyance and Treatment of Municipal Wastewater" (68) under Category IIB - Advanced Wastewater Treatment (AWT). The requirement for AWT generally exists where water quality standards require removal of such pollutants as phosphorus, ammonia, nitrate, and other substances. In addition, this AWT requirement exists where removal for conventional pollutants (BOD, solids) exceeds the Advanced Secondary Treatment (AST) level, i.e., 95 percent or 10/10 mg/L. It should be noted that a large number of plants designed for Advanced Secondary Treatment (AST) also have the capability for removing phosphorus and ammonia nitrogen.

Table 11 summarizes the projected facilities designed to provide advanced wastewater treatment (broken down into phosphorus, ammonia nitrogen, and total nitrogen removal) in the U.S. for the years 1980 and 2000.

It can be seen that the total wastewater flow of facilities requiring AWT is projected to increase five-fold from 2,840,000 m^3/d (750 mgd) in the year 1982 to 15,500,000 m^3/d (4,100 mgd) in the year 2000. Close to 60 percent of the total flow for AWT would involve phosphorus removal, while removal of ammonia nitrogen and total nitrogen would amount to 75 percent and 25 percent, respectively, of total AWT flow by the year 2000. The number of plants designed for phosphorus removal under AWT is projected to increase from 85 in the year 1980, to 263 in the year 2000. The number of plants designed for ammonia nitrogen removal under AWT is expected to increase from 116 in the year 1980, to 493 in the year 2000, while the corresponding number of plants for total nitrogen removal is 35 and 118. The sizes of these AWT plants range from less than 378 m^3/d (0.1 mgd) up to 189,250 m^3/d (50 mgd), with the average size being near 19,000 m^3/d (5 mgd) in 1980, and 30,000 m^3/d (8 mgd) in 2000. Therefore, the trend is toward building more large-size AWT plants between 1980 and 2000 than those that currently exist. From the data presented in Table 11, it appears that significant

TABLE 11. FACILITIES DESIGNED TO PROVIDE ADVANCED WASTEWATER TREATMENT (AWT) FOR ALL STATES AND U.S. TERRITORIES[1,2]

		Plants with removal capability								
		Phosphorus			NH_3-N			Total N		
	Total flow 1,000 m^3/d (mgd)	Number of plants[2]	Flow 1,000 m^3/d (mgd)	% of total flow	Number of plants[2]	Flow 1,000 m^3/d (mgd)	% of total flow	Number of plants	Flow 1,000 m^3/d (mgd)	% of total flow
Facilities in operation in 1980	2,845 (752)	85	1,653 (437)	58.1	116	1,389 (367)	48.8	35	574 (152)	20.1
Facilities to be in operation in 2000	15,626 (4,128)	263	9,301 (2,457)	59.5	493	11,726 (3,098)	75.1	118	3,888 (1,027)	24.8
Increment from 1980 to 2000	12,781 (3,376)	178	7,468 (2,020)	58.4	377	10,337 (2,731)	80.9	83	3,314 (875)	25.9
Average plant size in 1980	---	---	19.4 (5.1)	---	---	12.0 (3.2)	---	---	16.4 (4.3)	
Average plant size in 2000	---	---	35.4 (9.3)	---	---	23.8 (6.3)	---	---	33.0 (8.7)	

[1] From Reference 68, the "1980 Needs Survey."

[2] Does not include Advanced Secondary Treatment (AST) plants, which are for removal of BOD/TSS to the range of 10/10 to 24/24 mg/L, but also provide specific processes that remove phosphorus and/or ammonia in excess of the amounts normally removed by secondary treatment.

market potential exists for all three proprietary processes. Specifically, the greatest market potential exists in the following areas:

- Application of the PhoStrip process for phosphorus residual of 1 mg/L; for plant size above 19,000 m^3/d (5 mgd).
- Application of the A/O process for phosphorus residual of 2 mg/L; for all plant sizes.
- Application of the A/O process for phosphorus and ammonia nitrogen residuals of 1 and 2 mg/L, respectively; for all plant sizes.
- Application of the Bardenpho process for phosphorus and total nitrogen residuals of 2 and 3 mg/L, respectively; for all plant sizes.

COSTS AND ENERGY IMPACTS

The national dollar needs for upgrading/enlarging existing treatment plants and for construction of new advanced wastewater treatment (AWT) facilities are presented in Table 12 based on the "1980 Needs Survey" (68). The total incremental costs of AWT above the advanced secondary treatment (AST) level are estimated at $830 million in 1980 dollars. It is noted that these costs are for construction only and do not include costs for operation and maintenance. From comparison of total present worth costs presented in Tables 5 through 8, it can be seen that significant cost savings can be realized when either the PhoStrip, A/O, or Bardenpho process is used instead of the conventional (Baseline) process. The potential cost savings tends to increase when the plant size is increased. For plant size in the range of 18,925 to 189,250 m^3/d (5 to 50 mgd), savings in total present worth costs are estimated to be in the range of 10 to 25 percent on a total plant basis, depending on effluent requirements and the type of alternative process used. Savings in energy are expected to be less significant than in total present worth costs. As can be seen from Table 10, energy savings through the use of the three proprietary processes are generally less than 10 percent on a total plant basis, but can be as high as 20 percent, depending on the plant size, effluent requirements, and the type of alternative process used.

TABLE 12. NATIONAL DOLLAR NEEDS FOR CHANGES IN EXISTING TREATMENT PLANTS AND FOR CONSTRUCTION OF NEW ADVANCED WASTEWATER TREATMENT (AWT) FACILITIES[1]

Type	Number of plants	Total dollar needs[2], in millions of 1980 dollars
● Changes in existing plants		
- Planned changes by present design level of tertiary treatment for all facilities in operation in 1980	251	335.6
- Plants to be upgraded to tertiary treatment	16	10.3
- Plants to be enlarged and upgraded to tertiary treatment	11	49.7
Sub-total	278	395.6
● New tertiary treatment facilities	183	433.6
Total	461	829.2

[1] From Reference 68, the "1980 Needs Survey."

[2] Incremental costs above advanced secondary treatment (AST).

RISK ASSESSMENT

All three proprietary biological phosphorus removal processes have been reasonably well developed. Generally, they are capable of providing 1 to 2 mg/L of residual phosphorus. Therefore, the risk involved in using any of these processes is not in its complete failure, but in its capability to meet a specific set of effluent limitations. From available data presented in Tables 1, 2, and 3, it can be seen that these processes can be marginal, at times, in meeting the total phosphorus concentrations of 1 mg/L or 2 mg/L. Conducting pilot tests to obtain data for application in a specific case, prior to design, can minimize such risk.

Provision of additional facilities, such as the use of effluent filters and supplemental mineral addition, will further reduce the risk of not meeting the effluent requirements. However, such a provision would also reduce the benefit of cost savings that can be gained from the use of these alternative processes.

SECTION 6

RECOMMENDATIONS

FURTHER RESEARCH AND DEVELOPMENT EFFORTS

All three proprietary processes for biological phosphorus removal are based on the basic mechanism that utilizes the anaerobic treatment to pre-condition the microorganisms for subsequent enhanced uptake of phosphorus under aerobic conditions. Although significant data and experience have been obtained to substantiate the validity of the fundamental concept, numerous complex factors affecting the performance of the three different versions of biological phosphorus removal systems are not yet fully understood. Many researchers have raised a number of unanswered questions and expressed needs for further research and development, which have been put together in a perspective by Irvine, Stensel, and Alleman (1). Some of the more important aspects of research needs, including those identified by numerous researchers, as well as the opinions of the consultant, are listed in the following:

- Basic studies involving organisms selection, physiological states, survival, and the direct impact of the anaerobic zone must be conducted before biological phosphorus removal can be understood fully.

- Current design of the anaerobic section in each of the three proprietary processes appears to be empirical, and there is a lack of rational basis for sizing the anaerobic stage. The A/O system employs a relatively short detention time in the anaerobic zone and requires a sufficiently high input of soluble substrate to ensure rapid formation of anaerobic conditions. The Bardenpho system has a slightly longer detention time, but, as in the case of A/O, it also requires the presence of soluble substrate to establish adequate anaerobic conditions. (Some of the failures associated with the Bardenpho system have been related to low COD:TKN ratios in the feed to the system.) On the other hand, the PhoStrip process employs a relatively long SRT in the anaerobic stripper, which allows for hydrolysis of particulate organics contained in the portion of recycle sludge subjected to anaerobic treatment. Furthermore, introduction of dissolved oxygen and nitrate into the anaerobic zone has been found to interfere with biological phosphorus release in all three proprietary processes. The quantitative effects of these various factors on the sizing of the anaerobic tank need to be further delineated.

- The three biological phosphorus removal processes are capable of producing effluent total phosphorus of less than 2 mg/L; however, effluent total phosphorus concentrations of 1 to 2 mg/L appear in the marginal area that can hardly be predicted with certainty. The total phosphorus consists of soluble phosphorus as well as phosphorus associated with the suspended solids form. The soluble phosphorus in the effluent is related to the performance of the process employed, while the phosphorus in the solids form is related to the settling characteristics of sludge maintained in the system. Further research is necessary to develop a better basis for predicting effluent quality under various operating conditions and wastewater characteristics.

PROCESS/TECHNOLOGY MODIFICATIONS

All three processes discussed in this document have been well developed from the phosphorus removal standpoint. Potential improvements or modifications for each of the three processes are as follows:

- The PhoStrip process has been applied in conjunction with a two-stage activated sludge system to provide phosphorus and ammonia nitrogen removal. Nevertheless, the basis of design for necessary modifications in the PhoStrip process to integrate with biological nitrification/denitrification treatment systems needs to be further developed.

- Some modifications in the A/O process, possibly in the area of internal sludge recycle and more appropriate sizing of the anaerobic/anoxic/aerobic stages, may be necessary to demonstrate the capability of this process to achieve more satisfactory phosphorus removal and a higher degree of nitrification/denitrification than currently available.

- Some modifications in the Bardenpho process may be necessary to achieve more satisfactory performance in phosphorus and total nitrogen removal, particularly under the conditions of low COD:TKN ratio in the feed to the system.

REFERENCES

1. Irvine, R.L., H.D. Stensel, and J.E. Allenman. Summary Report, Workshop on Biological Phosphorus Removal in Municipal Wastewater Treatment, Annapolis, Maryland, June 22-24, 1982. Sponsored by U.S. EPA, Municipal Environmental Research Laboratory, Cincinnati, Ohio, September 1982.

2. U.S. EPA. Process Design Manual for Phosphorus Removal. EPA-625/1-76-001a, 1976.

3. Greenburg, A.E., G. Klein, and W.J. Kauffman. Effect of Phosphorus Removal on the Activated Sludge Process. Sewage Industrial Wastes, 27(3):277-282, 1955.

4. Srinath, E.G., C.A. Sastry, and S.C. Pillai. Rapid Removal of Phosphorus by Activated Sludge. Experimentia (Switzerland), 15:339, 1959.

5. Levin, G.V., and J. Shapiro. Metabolic Uptake of Phosphorus by Wastewater Organisms. Water Pollution Control Federation J., 37(6):800-821, 1965.

6. Shapiro, J., G.V. Levin, and Z.G. Humberto. Anoxically Induced Release of Phosphate in Sewage Treatment. Water Pollution Control Federation J., 39(11):1810-1818, 1967.

7. Vacker, D., C.H. Connel, and W.N. Wells. Phosphate Removal Through Municipal Wastewater Treatment at San Antonio, Texas. Water Pollution Control Federation J., 39(5):750-771, 1967.

8. Menar, A.B., and C. Jenkins. The Fate of Phosphorus in Waste Treatment Processes, The Enhanced Removal of Phosphate by Activated Sludge. In: Proceedings of the 24th Industrial Waste Treatment Conference, Purdue University, 1969.

9. Milbury, W.F., D. McCauly, and C.H. Hawthorne. Operation of Conventional Activated Sludge for Maximum Phosphorus Removal. Water Pollution Control Federation J., 43(9):1890-1901, 1971.

10. Garber, W.F. Phosphorus Removal by Chemical and Biological Mechanisms. Application of New Concepts of Physical Chemical Waste Water Treatment, Vanderbilt-University Conference, Pergamon Press, 1972.

11. Levin, G.V., G.J. Topol, A.G. Tarmy, and R.B. Samworth. Pilot Plant Tests of a Phosphorus Removal Process. Water Pollution Control Federation J., 44(10):1940-1954, 1972.

12. Levin, G.V., G.J. Topol, and A.G. Tarnay. Operation of a Full Scale Biological Phosphorus Removal Plant. Water Pollution Control Federation J., 47(3):577-590, 1975.

13. Levin, G.V., D.L. Masse, and J.J. Kish, Biospherics, Inc. The PhoStrip Process for Biological Removal of Phosphorus from Wastewater. Presented at EPA Workshop on Biological Phosphorus Removal in Municipal Wastewater Treatment, Annapolis, Maryland, 1982.

14. Barnard, J.L. Cut P and N Without Chemicals. Water and Wastes Engineering J., 11(7):33-36, 1974.

15. Refling, D.R., H.D. Stensel, D.E. Burns, and J.L. Barnard. Facility Modifications for Nutrient Removal Using the Bardenpho Process. Presented at the 50th Annual Water Pollution Control Federation Conference, Philadelphia, Pennsylvania, 1977.

16. Krichten, D.J., D.M. Nicholas, and J.V. Galdiers. Phosphorus and BOD Removal in an Activated Sludge System Without Chemical Addition. Presented at the 176th National Meeting, American Chemical Society, Miami Beach, Florida, 1978.

17. Hong, S.N., D.J. Krichten, K.S. Kisenbauer, and R.L. Sell. A Biological Wastewater Treatment System for Nutrient Removal. Presented at the Workshop on Biological Phosphorus Removal in Municipal Wastewater Treatment, Annapolis, Maryland, 1982.

18. Siebritz, J.P., G.A. Ekama, and G.V.A. Marais. A Parametric Model for Biological Excess Phosphorus Removal. Presented at the Post Conference Seminar on Phosphate Removal in Biological Treatment Processes, International Association on Water Pollution Research, Pretoria, South Africa, 1982.

19. Mulbarger, M.C., and R. Prober. A Consultant's Perspective. Presented at the Workshop on Biological Phosphorus Removal in Municipal Wastewater Treatment, Annapolis, Maryland, 1982.

20. Barth, E.F., and H.D. Stensel. International Nutrient Control Technology for Municipal Effluents. Water Pollution Control Federation J., 53(12):1691-1701, 1981.

21. U.S. EPA. Innovative and Alternative Technology Assessment Manual. MCD-53, EPA 430/9-78-009, 1980.

22. Smith, J.M., J.J. McCarthy, and H.L. Longest. Impact of Innovative and Alternative Technology in the United States in the 1980's. U.S. EPA, Municipal Environmental Research Laboratory, Cincinnati, Ohio, 1980.

23. Peirano, L.E. Low Cost Phosphorus Removal at Reno-Sparks, Nevada. Water Pollution Control Federation J., 46(4):568-574, 1977.

24. Drnevich, R.F. Biological-Chemical Process for Removing Phosphorus at Reno-Sparks, Nevada. EPA-600/2-79-007, U.S. EPA, 1979.

25. Peirano, L.E., D.B. Henderson, J.G.M. Gonzales, and E.F. Davis. Full-Scale Experiences with the PhoStrip Process. Presented at Post Conference Seminar on Phosphate Removal in Biological Treatment Processes, International Association on Water Pollution Research, Pretoria, South Africa, 1982.

26. Campbell, T.L., J.M. Reece, T.J. Murphy, and R.F. Drnevich. Biological Phosphorus Removal at Brockton, Massachusetts. New England Water Pollution Control Association J., 12(1): 61-73, 1978.

27. Drnevich, R.F., and L.C. Matsch. A Process for Simultaneous Phosphorus and Nitrogen Removal. Presented at the 51st Annual Conference of the Water Pollution Control Association, Anaheim, California, 1978.

28. Miyamoto-Mills, J., J. Larson, D. Jenkins, and W. Owen. Design and Operation of a Pilot-Scale Biological Phosphate Removal Plant at the Central Contra Costa Sanitary District. Presented at Post Conference Seminar on Phosphate Removal in Biological Treatment Processes, International Association on Water Pollution Research, Pretoria, South Africa, 1982.

29. Dedyo, J., and R. Doan. Reduced Energy Usage with Biological Phosphorus Removal. Water Pollution Control Federation J., 53(7):1116-1171, 1981.

30. Roy F. Weston, Inc. I/A Technology Assessment Post Construction Evaluation of Amherst, New York, PhoStrip Facility. EPA Contract No. 68-03-3055, U.S. EPA, Draft Report, 1983.

31. Levin, G.V., Biospherics, Inc., undated.

32. Galdieri, J.V. Biological Phosphorus Removal. Chemical Engineering J., 86(28):34-35, 1979.

33. Air Products and Chemicals, Inc. Wastewater Treatment with Nutrient Removal, the A/O System. Catalog No. 210-101, 1981.

34. Hong, S.N., K.S. Kisenbauer, and V.G. Fox. An Innovative Biological Nutrient Removal System. In: Proceedings of the Conference on Environmental Engineering, ASCE, Atlanta, Georgia, 1981.

35. Krichten, D.J., and S.N. Hong. Biological Nutrient Control Plant Demonstration. In: Proceedings of WATER FORUM '81, ASCE, San Francisco, California, 1981.

36. Krichten, D.J., Air Products and Chemicals, Inc. Information provided to Roy F. Weston, Inc., August 2, 1982.

37. Stensel, H.D., N. Sakakibara, D.R. Refling, and C.R. Burdick. Performance of First U.S. Full-Scale Bardenpho Facility. Presented at the EPA International Seminar on Control of Nutrients in Municipal Wastewater Effluents, San Diego, California, 1980.

38. Burdick, C.R., D.R. Refling, and H.D. Stensel. Advanced Biological Treatment to Achieve Nutrient Removal. Water Pollution Control Federation J., 54(7):1078-1086, 1982.

39. Burdick, C.R., and G. Dallaire. Florida Sewage Plant First to Remove Nutrients with Bacteria Alone - No Need for Costly Chemicals. Civil Engineering J., ASCE, 48(10): 51-56, 1978.

40. Barnard, J.L. Biological Nutrient Removal Without the Addition of Chemicals. Water Research J., 9:485-490, 1975.

41. Buchan, L. Possible Biological Mechanism of Phosphorus Removal. Presented at Post Conference Seminar on Phosphate Removal in Biological Treatment Processes, International Association on Water Pollution Research, Pretoria, South Africa, 1982.

42. Barnard, J.L., and D.W. Osborn. Advanced Solutions to Pollution Problems in South Africa. Presented at the Water Pollution Control Federation Conference, Miami, Florida, 1975.

43. Stensel, H.D., and J.H. Scott. Cost-Effective Advanced Biological Wastewater Treatment Systems. Presented at the Nevada Water Pollution Control Association Annual Meeting, 1977.

44. Paepeke, B.H. Performance and Operational Aspects of Biological Phosphate Removal Plants in South Africa. Presented at the Post Conference Seminar on Phosphate Removal in Biological Treatment Processes, International Association on Water Pollution Research, Pretoria, South Africa, 1982.

45. Barnard, J.L. Design Consideration Regarding Phosphate Removal in Activated Sludge Plants. Presented at the Post Conference Seminar on Phosphate Removal in Biological Treatment Processes, International Association on Water Pollution Research, Pretoria, South Africa, 1982.

46. Pitman, A.R., S.L.V. Venter, and H.A. Nicholls. Practical Experience with Biological Phosphorus Removal Plants in Johannesburg. Presented at the Post Conference Seminar on Phosphate Removal in Biological Treatment Processes, International Association on Water Pollution Research, Pretoria, South Africa, 1982.

47. McCarty, P.L. Phosphorus and Nitrogen Removal by Biological Systems. Presented at the 2nd Annual Sanitary Engineering Research Laboratory Workshop, Wastewater Reclamation and Reuse, Tahoe City, California, 1970.

48. Harold, F.M. Inorganic Polyphosphates in Biology: Structure, Metabolism, and Function. Bacteriology Reviews, 30:776, 1966.

49. Sell, R.L., D.J. Krichten, O.J. Noichl, and D.G. Harzog. Low Temperature Biological Phosphorus Removal. Presented at the 54th Annual Water Pollution Control Conference, Detroit, Michigan, 1981.

50. Buchan, L. The Location and Nature of Accumulated Phosphorus in Seven Sludges from Activated Sludge Plants which Exhibited Enhanced Phosphorus Removal. Water SA, 7:1, 1981.

51. Mudd, S. Polyphosphate as Accumulator of Phosphorus and Energy. Bacteriology J., 75:224, 1958.

52. Timmerman, M.W. Biological Phosphate Removal from Domestic Wastewater Using Anaerobic/Aerobic Treatment. Chapter 26 of "Development of Industrial Microbiology," 20:285, 1979.

53. Nicholls, H.A., and D.W. Osborn. Bacterial Stress: Prerequisite for Biological Removal of Phosphorus. Water Pollution Control Federation J., 51(3):557-569, 1979.

54. Lawson, E.N., and N.E. Tonhazy. Changes in Morphology and Phosphate-Uptake Patterns of *Acinetobacter calcoaceticus* strains. Water SA, 6:105, 1980.

55. Deinema, M.H., et al. The Accumulation of Polyphosphate in *Acinetobacter Spp*. Microbiology Letters, Federation of Microbiological Societies, 273-279, 1980.

56. Senior, P.J., et al. The Role of Oxygen Limitation in the Formation of Poly B Hydroxybutyrate during Batch and Continuous Culture of *Azotobacter beijerincku*. Biochemistry J., 128: 1193, 1972.

57. Hong, S.N., et al. A Biological Wastewater Treatment for Nutrient Removal. Presented at the 54th Annual Water Pollution Control Federation, Detroit, Michigan, 1981.

58. Rensank, J.H., H.J.G.W. Donker, and H.P. deVries. Biological P-Removal in Domestic Wastewater by the Activated Sludge Process. Presented at the 5th European Sewage and Refuse Symposium, Munchen, Procs. 487-502, 1981.

59. Gaudy, A., and E. Gaudy. Microbiology for Environmental Scientists and Engineers. McGraw-Hill Book Co., 1980.

60. Marais, G.V.R., R.E. Loewenthal, and I. Siebritz. Review: Observations Supporting Phosphate Removal by Biological Excess Uptake. Selected Papers on Activated Sludge Process Research at the University of Capetown, South Africa, 1981.

61. Fuhs, G.W., and M. Chen. Microbial Basis of Phosphate Removal in the Activated Sludge Process for the Treatment of Wastewater. Microb. Ecol. 2:119-138, 1975.

62. Brodish, K.E.U., and S.J. Joyner. The Role of Microorganisms Other Than *Acinetobacter* in Biological Phosphorus Removal in Activated Sludge Processes. Presented at Post Conference Seminar on Phosphate Removal in Biological Treatment Processes, International Association on Water Pollution Research, Pretoria, South Africa, 1982.

63. Osborn, D.W., and H.A. Nicholls. Optimization of the Activated Sludge Process for the Biological Removal of Phosphorus. Presented at the International Conference on Advanced Treatment and Reclamation of Wastewater, Johannesburg, South Africa, 1977.

64. Stensel H.D. Biological Nitrogen Removal System Design. American Institute of Chemical Engineers, Water, Vol. 70, Number 209, 1980.

65. Knowles, G., et al. Determination of Kinetic Constants for Nitrifying Bacteria in Mixed Culture with the Aid of an Electronic Computer. Gen. Microbiology J., 38:263, 1965.

66. U S. EPA. Innovative and Alternative Technology Assessment Manual. MCD-53, EPA-430/9-78-009, 1980.

67. U.S. EPA. Areawide Assessment Procedures Manual. Vol. III, EPA-600/9-76-014, 1976.

68. U.S. EPA. The 1980 Needs Survey, Conveyance, Treatment, and Control of Municipal Wastewater, Combined Sewer Overflows, and Stormwater Runoff, Summaries of Technical Data. EPA-430/9-81-008, FRD 23, 1981.

APPENDIX A

COST AND ENERGY ANALYSIS -- ASSUMPTIONS

In order to compare the various alternatives, a basis for the cost comparison was required. The major sources of costs (capital, and operations and maintenance) and energy requirement data were the Innovative and Alternative (I&A) Technology Assessment Manual (66), with additional input from the Areawide Assessment Procedures Manual, Appendix H (67). Costs for the A/O and Bardenpho processes were developed based on preliminary concept design and WESTON's in-house cost estimates.

In order to accommodate the specific design conditions, numerous assumptions were required to adjust and extrapolate cost data that will reflect the specific design case. The assumptions utilized for technology evaluation are as follows:

- Construction costs were updated to October 1982 utilizing the Engineering News Record (ENR) Construction Cost Index of 3875.
- Operation and maintenance costs were updated to October 1982 utilizing EPA's Escalation Index of 3.55 and electrical energy cost of $0.05/kwh.
- Construction costs were upgraded to capital costs by inclusion of noncomponent costs. The noncomponent costs and the percentage of construction costs used are as follows:

Item	Percent
Piping	10
Electrical	8
Instrumentation	5
Site Preparation	5

- Engineering services and contingency costs were each assumed to be 15 percent of the capital cost. The sum of the construction costs, noncomponent costs, engineering services, and contingency yielded the total installed capital cost.

- For present worth analysis, all equipment was assumed to have a 20-year service life (zero salvage or replacement cost over cost-effectiveness time period), and present worth was equal to the sum of capital cost plus present worth of annual O&M costs. A discount rate of 7-5/8 percent, which was effective as of October 1982, was assumed. Present worth factor = 10.0983.

- For each of the alternative cases shown in Table 4, costs were developed for the following three plant sizes:

1,892 m^3/d	(0.5 mgd)
18,925 m^3/d	(5.0 mgd)
189,250 m^3/d	(50.0 mgd)

- Influent wastewater characteristics were assumed as follows:

  BOD_5 = 210 mg/L
  TSS = 230 mg/L
  VSS = 172 mg/L
  TP = 10 mg/L
  TKN = 35 mg/L
  NH_3N = 20 mg/L

- Preliminary treatment (including bar screens and grit chambers) and primary clarifiers were assumed to precede the biological treatment. The primary clarifiers were assumed to provide 60 percent TSS, 35 percent BOD, 10 percent TP, and 14 percent TKN removal.

- The baseline technology for BOD, TSS, and phosphorus removal was assumed to be conventional activated sludge with alum addition. This baseline technology was compared with the PhoStrip and A/O processes. To produce effluent TP of 1 mg/L, additional effluent filters were assumed to be required for the A/O process in Case 1.

- The baseline technology for BOD, TSS, phosphorus, and ammonia nitrogen removal was assumed to be high rate activated sludge followed by nitrification activated sludge with separate clarifiers in each of the two stages. This baseline technology was compared with the A/O process.

- The baseline technology for BOD, TSS, phosphorus, and total nitrogen removal was assumed to be high rate activated sludge, followed by nitrification activated sludge, and by denitrification activated sludge with separate clarifiers in each of the three stages. This baseline technology was compared with the Bardenpho process. In both cases, effluent filtration would be required to achieve a TN residual of 3 mg/L, but since the cost would be the same for both, filtration was not included in the comparison.

- The design conditions for the PhoStrip process were assumed to be the same as those indicated in Fact Sheet 2.1.17 of the I&A Manual (66).

- The A/O process design detention times were assumed to be as follows:

Stage	Detention time, hours TP removal	 TP & NH_3-N removal
Anaerobic (3-stage)	1.0	1.0
Anoxic (3-stage)	---	1.0
Oxic (aerobic, 4-stage)	3.0	4.0
Total	4.0	6.0

MLSS = 2,000 mg/L

Internal flow recycle from oxic to anoxic stage = 200 percent (for A/O with nitrification)

- To minimize the return of phosphorus contained in the sidestreams of the A/O Process, an additional lime dosage of 7.9 kg/1,000 m^3 (66 lbs/million gallons) was assumed for aerobically-digested sludge, and 30 kg/1,000 m^3 (250 lbs/million gallons) was assumed for anaerobically-digested sludge.

- The Bardenpho process design detention times were assumed to be as follows:

Stage	Detention time, hours
Anaerobic	1.5
First anoxic	4.0
Aeration (nitrification)	6.5
Second anoxic	3.0
Reaeration	1.0
Total	16.0

  MLSS = 3,500 mg/L

  Internal flow recycle from the aeration to first anoxic stage = 400 percent

- The excess biological sludge from the Bardenpho process was assumed to require no further digestion since the solids residence time (SRT) in the system was estimated at 27 days under design conditions.

- The anaerobic and anoxic tanks in the A/O or Bardenpho processes are to be covered.

- Surface mechanical aerators were assumed to be used in the aerobic stages. Maximum aerator capacity of 1.5 times the daily average requirement was provided. Mixing power of 10 kw/1,000 m^3 (50 hp/million gallons) tank capacity was assumed in all anaerobic and anoxic stages.

- For the Bardenpho process and A/O with nitrification and partial denitrification, the amount of oxygen required is estimated to be reduced by 2.8 times the amount of nitrate nitrogen (NH_3-N) denitrified.

- The primary sludge was assumed to have a solids concentration of 4 percent from the clarifier underflow. The waste activated sludge was assumed to have a solids concentration of 0.8 percent (except 1.5 percent in the case of A/O) from the clarifier underflow. The waste activated sludge was to be further thickened to a minimum of 4 percent by dissolved air flotation (DAF) prior to combining with the primary sludge for digestion, except at 1,892 m^3/d (0.5 mgd).

- All the primary and waste activated sludge (except the Bardenpho sludge) was assumed to require further stabilization by digestion. Aerobic digestion was assumed for the 1,892 m^3/d (0.5 mgd) and 18,925 m^3/d (5.0 mgd) size plants; anaerobic digestion was assumed for the 189,250 m^3/d (50 mgd) size plant.

- Dewatering via sludge drying beds was assumed for the 1,892 m^3/d (0.5 mgd) size plant, and dewatering via vacuum filters was assumed for the 18,925 m^3/d (5.0 mgd) and 189,250 m^3/d (50.0 mgd) size plants.

- For all alternative cases, the dewatered sludge was assumed to be transported by trucks for a one-way distance of 1.6 km (10 miles) and disposed of in a sanitary landfill. Appropriate assumptions as to sludge generation rates for various cases were assumed to allow for sludge volume calculations. Energy requirements were modified from data presented in the I&A Manual.

APPENDIX B

COST COMPARISON AND ENERGY ANALYSIS

Tables B-1 through B-12 deal with cost comparison of the various facility sizes; Tables B-13 through B-24 present an energy analysis for the same facilities.

TABLE B-1. COST COMPARISON -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

CASE 1
PHOSPHORUS REMOVAL (EFFLUENT TP = 1 mg/L)
ENR INDEX = 3875

Process unit	Alternative 1-A one-stage activated sludge with alum addition (baseline)	Alternative 1-B PhoStrip	Alternative 1-C A/O
Low Lift Pumping	$ 188,000	$ 188,000	$ 188,000
Preliminary Treatment	47,000	47,000	47,000
Primary Treatment	122,000	122,000	122,000
Aeration/Clarification	447,000	447,000	501,000
PhoStrip (with Lime Addition)	---	595,000	---
Chemical Addition	31,000	---	5,000
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	63,000	63,000	63,000
Effluent Filtration	---	---	297,000
Gravity Outfall	96,000	96,000	96,000
Miscellaneous Structures	78,000	78,000	78,000
Thickening (DAF)	---	---	---
Digestion (Aerobic)	125,000	125,000	130,000
Dewatering (Drying Bed)	78,000	66,000	66,000
Sludge Hauling/Landfilling	204,000	200,000	204,000
Sub-Total	$1,479,000	$2,027,000	$1,797,000
Noncomponent Costs[2]	414,000	568,000	503,000
Engineering and Construction Supervision	284,000	389,000	345,000
Contingency	284,000	389,000	345,000
TOTAL CAPITAL COSTS	$2,461,000	$3,373,000	$2,990,000
ANNUAL O&M COSTS	$ 202,000	$ 253,000	$ 210,000
TOTAL PRESENT WORTH COSTS[3]	$4,501,000	$5,928,000	$5,111,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-2. COST COMPARISON -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

CASE 1
PHOSPHORUS REMOVAL (EFFLUENT TP = 1 mg/L)
ENR INDEX = 3875

Process unit	Alternative 1-A one-stage activated sludge with alum addition (baseline)	Alternative 1-B PhoStrip	Alternative 1-C A/O
Low Lift Pumping	$ 705,000	$ 705,000	$ 705,000
Preliminary Treatment	196,000	196,000	196,000
Primary Treatment	438,000	438,000	438,000
Aeration/Clarification	2,035,000	2,035,000	2,129,000
PhoStrip (with Lime Addition)	---	1,096,000	12,000
Chemical Addition	78,000	---	---
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	191,000	191,000	191,000
Effluent Filtration	---	---	1,300,000
Gravity Outfall	310,000	310,000	310,000
Miscellaneous Structures	250,000	250,000	250,000
Thickening (DAF)	204,000	188,000	196,000
Digestion (Aerobic)	470,000	470,000	500,000
Dewatering (Vacuum Filter)	658,000	595,000	595,000
Sludge Hauling/Landfilling	251,000	246,000	247,000
Sub-Total	$ 5,786,000	$ 6,720,000	$ 7,069,000
Noncomponent Costs[2]	1,620,000	1,882,000	1,979,000
Engineering and Construction Supervision	1,111,000	1,290,000	1,357,000
Contingency	1,111,000	1,290,000	1,357,000
TOTAL CAPITAL COSTS	$ 9,628,000	$11,182,000	$11,763,000
ANNUAL O&M COSTS	$ 805,000	$ 690,000	$ 775,000
TOTAL PRESENT WORTH COSTS[3]	$17,757,000	$18,150,000	$19,589,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-3. COST COMPARISON -- 189,250 m^3/d (50.0 mgd) FACILITY[1]

CASE 1
PHOSPHORUS REMOVAL (EFFLUENT TP = 1 mg/L)
ENR INDEX = 3875

Process unit	Alternative 1-A one-stage activated sludge with alum addition (baseline)	Alternative 1-B PhoStrip	Alternative 1-C A/O
Low Lift Pumping	$ 3,600,000	$ 3,600,000	$ 3,600,000
Preliminary Treatment	783,000	783,000	783,000
Primary Treatment	2,270,000	2,270,000	2,270,000
Aeration/Clarification	12,995,000	12,995,000	11,797,000
PhoStrip (with Lime Addition)	---	2,740,000	---
Chemical Addition	579,000	---	230,000
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	798,000	798,000	798,000
Effluent Filtration	---	---	5,950,000
Gravity Outfall	1,190,000	1,190,000	1,190,000
Miscellaneous Structures	1,000,000	1,000,000	1,000,000
Thickening (DAF)	391,000	344,000	360,000
Digestion (Aerobic)	2,740,000	2,740,000	2,818,000
Dewatering (Vacuum Filter)	2,818,000	2,583,000	2,583,000
Sludge Hauling/Landfilling	467,000	457,000	467,000
Sub-Total	$ 29,631,000	$31,500,000	$33,846,000
Noncomponent Costs[2]	8,297,000	8,820,000	9,477,000
Engineering and Construction Supervision	5,689,000	6,048,000	6,498,000
Contingency	5,689,000	6,048,000	6,498,000
TOTAL CAPITAL COSTS	$ 49,306,000	$52,416,000	$56,319,000
ANNUAL O&M COSTS	$ 5,200,000	$ 3,666,000	$ 4,212,000
TOTAL PRESENT WORTH COSTS[3]	$101,817,000	$89,436,000	$98,853,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-4. COST COMPARISON -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

CASE 2
PHOSPHORUS REMOVAL (EFFLUENT TP = 2 mg/L)
ENR INDEX = 3875

Process unit	Alternative 2-A one-stage activated sludge with alum addition (baseline)	Alternative 2-B PhoStrip	Alternative 2-C A/O
Low Lift Pumping	$ 188,000	$ 188,000	$ 188,000
Preliminary Treatment	47,000	47,000	47,000
Primary Treatment	122,000	122,000	122,000
Aeration/Clarification	447,000	447,000	501,000
PhoStrip (with Lime Addition)	---	595,000	---
Chemical Addition	25,000	---	5,000
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	63,000	63,000	63,000
Effluent Filtration	---	---	---
Gravity Outfall	96,000	96,000	96,000
Miscellaneous Structures	78,000	78,000	78,000
Thickening (DAF)	---	---	---
Digestion (Aerobic)	125,000	125,000	130,000
Dewatering (Drying Bed)	78,000	66,000	66,000
Sludge Hauling/Landfilling	204,000	200,000	204,000
Sub-Total	$1,473,000	$2,027,000	$1,500,000
Noncomponent Costs[2]	412,000	568,000	420,000
Engineering and Construction Supervision	283,000	389,000	288,000
Contingency	283,000	389,000	288,000
TOTAL CAPITAL COSTS	$2,451,000	$3,373,000	$2,496,000
ANNUAL O&M COSTS	$ 197,000	$ 253,000	$ 183,000
TOTAL PRESENT WORTH COSTS[3]	$4,440,000	$5,928,000	$4,344,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-5. COST COMPARISON -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

CASE 2
PHOSPHORUS REMOVAL (EFFLUENT TP = 2 mg/L)
ENR INDEX = 3875

Process unit	Alternative 2-A one-stage activated sludge with alum addition (baseline)	Alternative 2-B PhoStrip	Alternative 2-C A/O
Low Lift Pumping	$ 705,000	$ 705,000	$ 705,000
Preliminary Treatment	196,000	196,000	196,000
Primary Treatment	438,000	438,000	438,000
Aeration/Clarification	2,035,000	2,035,000	2,129,000
PhoStrip (with Lime Addition)	---	1,096,000	---
Chemical Addition	62,000	---	12,000
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	191,000	191,000	191,000
Effluent Filtration	---	---	---
Gravity Outfall	310,000	310,000	310,000
Miscellaneous Structures	250,000	250,000	250,000
Thickening (DAF)	204,000	188,000	196,000
Digestion (Aerobic)	470,000	470,000	500,000
Dewatering (Vacuum Filter)	658,000	595,000	595,000
Sludge Hauling/Landfilling	251,000	246,000	247,000
Sub-Total	$ 5,770,000	$ 6,720,000	$ 5,769,000
Noncomponent Costs[2]	1,616,000	1,882,000	1,615,000
Engineering and Construction Supervision	1,108,000	1,290,000	1,108,000
Contingency	1,108,000	1,290,000	1,108,000
TOTAL CAPITAL COSTS	$ 9,602,000	$11,182,000	$ 9,600,000
ANNUAL O&M COSTS	$ 774,000	$ 690,000	$ 641,000
TOTAL PRESENT WORTH COSTS[3]	$17,418,000	$18,150,000	$16,073,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-6. COST COMPARISON -- 189,250 m^3/d (50.0 mgd) FACILITY[1]

CASE 2
PHOSPHORUS REMOVAL (EFFLUENT TP = 2 mg/L)
ENR INDEX = 3875

Process unit	Alternative 2-A one-stage activated sludge with alum addition (baseline)	Alternative 2-B PhoStrip	Alternative 2-C A/O
Low Lift Pumping	$ 3,600,000	$ 3,600,000	$ 3,600,000
Preliminary Treatment	783,000	783,000	783,000
Primary Treatment	2,270,000	2,270,000	2,270,000
Aeration/Clarification	12,995,000	12,995,000	11,797,000
PhoStrip (with Lime Addition)	---	2,740,000	---
Chemical Addition	463,000	---	230,000
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	798,000	798,000	798,000
Effluent Filtration	---	---	---
Gravity Outfall	1,190,000	1,190,000	1,190,000
Miscellaneous Structures	1,000,000	1,000,000	1,000,000
Thickening (DAF)	391,000	344,000	360,000
Digestion (Aerobic)	2,740,000	2,740,000	2,818,000
Dewatering (Vacuum Filter)	2,818,000	2,583,000	2,583,000
Sludge Hauling/Landfilling	467,000	457,000	467,000
Sub-Total	$29,515,000	$31,500,000	$27,896,000
Noncomponent Costs[2]	8,264,000	8,820,000	7,811,000
Engineering and Construction Supervision	5,667,000	6,048,000	5,356,000
Contingency	5,667,000	6,048,000	5,356,000
TOTAL CAPITAL COSTS	$49,113,000	$52,416,000	$46,419,000
ANNUAL O&M COSTS	$ 4,890,000	$ 3,666,000	$ 3,540,000
TOTAL PRESENT WORTH COSTS[3]	$98,494,000	$89,436,000	$82,167,000

[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-7. COST COMPARISON -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

CASE 3
PHOSPHORUS REMOVAL AND NITRIFICATION
(EFFLUENT TP = 2 mg/L, NH_3-N = 1 mg/L)
ENR INDEX = 3875

Process unit	Alternative 3-A two-stage activated sludge with alum addition (baseline)	Alternative 3-C A/O[4]
Low Lift Pumping	$ 188,000	$ 188,000
Preliminary Treatment	47,000	47,000
Primary Treatment	122,000	122,000
Aeration/Clarification	411,000	676,000
PhoStrip	---	---
Chemical Addition	25,000	5,000
Nitrification/Clarification	360,000	---
Denitrification/Clarification	---	---
Chlorination	63,000	63,000
Effluent Filtration	---	---
Gravity Outfall	96,000	96,000
Miscellaneous Structures	78,000	78,000
Thickening (DAF)	---	---
Digestion (Aerobic)	125,000	130,000
Dewatering (Drying Bed)	78,000	66,000
Sludge Hauling/Landfilling	204,000	204,000
Sub-Total	$1,797,000	$1,675,000
Noncomponent Costs[2]	503,000	469,000
Engineering and Construction Supervision	345,000	322,000
Contingency	345,000	322,000
TOTAL CAPITAL COSTS	$2,990,000	$2,788,000
ANNUAL O&M COSTS	$ 227,000	$ 195,000
TOTAL PRESENT WORTH COSTS[3]	$5,282,000	$4,757,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

[4] A/O also provides partial denitrification (effluent TN = 10 mg/L, NO_3-N = 8 mg/L).

TABLE B-8. COST COMPARISON -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

CASE 3
PHOSPHORUS REMOVAL AND NITRIFICATION
(EFFLUENT TP = 2 mg/L, NH_3-N = 1 mg/L)
ENR INDEX = 3875

Process unit	Alternative 3-A two-stage activated sludge with alum addition (baseline)	Alternative 3-C A/O[4]
Low Lift Pumping	$ 705,000	$ 705,000
Preliminary Treatment	196,000	196,000
Primary Treatment	438,000	438,000
Aeration/Clarification	1,614,000	2,728,000
PhoStrip	---	---
Chemical Addition	62,000	12,000
Nitrification/Clarification	1,487,000	---
Denitrification/Clarification	---	---
Chlorination	191,000	191,000
Effluent Filtration	---	---
Gravity Outfall	310,000	310,000
Miscellaneous Structures	250,000	250,000
Thickening (DAF)	204,000	196,000
Digestion (Aerobic)	470,000	500,000
Dewatering (Vacuum Filter)	658,000	595,000
Sludge Hauling/Landfilling	251,000	247,000
Sub-Total	$ 6,836,000	$ 6,368,000
Noncomponent Costs[2]	1,914,000	1,783,000
Engineering and Construction Supervision	1,313,000	1,223,000
Contingency	1,313,000	1,223,000
TOTAL CAPITAL COSTS	$11,376,000	$10,596,000
ANNUAL O&M COSTS	$ 854,000	$ 702,000
TOTAL PRESENT WORTH COSTS[3]	$20,000,000	$17,685,000

[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

[4] A/O also provides partial denitrification (effluent TN = 10 mg/L, NO_3-N = 8 mg/L).

TABLE B-9. COST COMPARISON -- 189,250 m^3/d (50.0 mgd) FACILITY[1]

CASE 3
PHOSPHORUS REMOVAL AND NITRIFICATION
(EFFLUENT TP = 2 mg/L, NH_3-N = 1 mg/L)
ENR INDEX = 3875

Process unit	Alternative 3-A two-stage activated sludge with alum addition (baseline)	Alternative 3-C A/O[4]
Low Lift Pumping	$ 3,600,000	$ 3,600,000
Preliminary Treatment	783,000	783,000
Primary Treatment	2,270,000	2,270,000
Aeration/Clarification	8,510,000	15,452,000
PhoStrip	---	---
Chemical Addition	463,000	230,000
Nitrification/Clarification	8,768,000	---
Denitrification/Clarification	---	---
Chlorination	798,000	798,000
Effluent Filtration	---	---
Gravity Outfall	1,190,000	1,190,000
Miscellaneous Structures	1,000,000	1,000,000
Thickening (DAF)	391,000	360,000
Digestion (Aerobic)	2,740,000	2,818,000
Dewatering (Vacuum Filter)	2,818,000	2,583,000
Sludge Hauling/Landfilling	467,000	467,000
Sub-Total	$ 33,798,000	$31,551,000
Noncomponent Costs[2]	9,463,000	8,834,000
Engineering and Construction Supervision	6,489,000	6,058,000
Contingency	6,489,000	6,058,000
TOTAL CAPITAL COSTS	$ 56,239,000	$52,501,000
ANNUAL O&M COSTS	$ 5,369,000	$ 3,952,000
TOTAL PRESENT WORTH COSTS[3]	$110,457,000	$92,409,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

[4] A/O also provides partial denitrification (effluent TN = 10 mg/L, NO_3-N = 8 mg/L).

TABLE B-10. COST COMPARISON -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

CASE 4
PHOSPHORUS REMOVAL, NITRIFICATION, AND DENITRIFICATION (EFFLUENT TP = 2 mg/L, TN = 3 mg/L)
ENR INDEX = 3875

Process unit	Alternative 4-A three-stage activated sludge with alum addition (baseline)	Alternative 4-D Bardenpho
Low Lift Pumping	$ 188,000	$ 188,000
Preliminary Treatment	47,000	47,000
Primary Treatment	122,000	122,000
Aeration/Clarification	411,000	835,000
PhoStrip	---	---
Chemical Addition	25,000	---
Nitrification/Clarification	360,000	---
Denitrification/Clarification	266,000	---
Chlorination	63,000	63,000
Effluent Filtration	---	---
Gravity Outfall	96,000	96,000
Miscellaneous Structures	78,000	78,000
Thickening (DAF)	---	---
Digestion (Aerobic)	125,000	94,000
Dewatering (Drying Bed)	78,000	67,000
Sludge Hauling/Landfilling	204,000	181,000
Sub-Total	$2,063,000	$1,771,000
Noncomponent Costs[2]	578,000	496,000
Engineering and Construction Supervision	396,000	340,000
Contingency	396,000	340,000
TOTAL CAPITAL COSTS	$3,433,000	$2,947,000
ANNUAL O&M COSTS	$ 274,000	$ 190,000
TOTAL PRESENT WORTH COSTS[3]	$6,200,000	$4,866,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-11. COST COMPARISON -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

CASE 4
PHOSPHORUS REMOVAL, NITRIFICATION, AND DENITRIFICATION
(EFFLUENT TP = 2 mg/L, TN = 3 mg/L)
ENR INDEX = 3875

Process unit	Alternative 4-A three-stage activated sludge with alum addition (baseline)	Alternative 4-D Bardenpho
Low Lift Pumping	$ 705,000	$ 705,000
Preliminary Treatment	196,000	196,000
Primary Treatment	438,000	438,000
Aeration/Clarification	1,614,000	3,815,000
PhoStrip	---	---
Chemical Addition	62,000	---
Nitrification/Clarification	1,487,000	---
Denitrification/Clarification	924,000	---
Chlorination	191,000	191,000
Effluent Filtration	---	---
Gravity Outfall	310,000	310,000
Miscellaneous Structures	250,000	250,000
Thickening (DAF)	204,000	164,000
Digestion (Aerobic)	470,000	344,000
Dewatering (Vacuum Filter)	658,000	595,000
Sludge Hauling/Landfilling	251,000	219,000
Sub-Total	$ 7,760,000	$ 7,227,000
Noncomponent Costs[2]	2,173,000	2,024,000
Engineering and Construction Supervision	1,490,000	1,388,000
Contingency	1,490,000	1,388,000
TOTAL CAPITAL COSTS	$12,913,000	$12,026,000
ANNUAL O&M COSTS	$ 1,112,000	$ 701,000
TOTAL PRESENT WORTH COSTS[3]	$24,142,000	$19,105,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-12. COST COMPARISON -- 189,250 m^3/d (50.0 mgd) FACILITY[1]

CASE 4
PHOSPHORUS REMOVAL, NITRIFICATION, AND DENITRIFICATION
(EFFLUENT TP = 2 mg/L, TN = 3 mg/L)
ENR INDEX = 3875

Process unit	Alternative 4-A three-stage activated sludge with alum addition (baseline)	Alternative 4-D Bardenpho
Low Lift Pumping	$ 3,600,000	$ 3,600,000
Preliminary Treatment	783,000	783,000
Primary Treatment	2,270,000	2,270,000
Aeration/Clarification	8,510,000	26,460,000
PhoStrip	---	---
Chemical Addition	463,000	---
Nitrification/Clarification	8,768,000	---
Denitrification/Clarification	5,010,000	---
Chlorination	798,000	798,000
Effluent Filtration	---	---
Gravity Outfall	1,190,000	1,190,000
Miscellaneous Structures	1,000,000	1,000,000
Thickening (DAF)	391,000	297,000
Digestion (Aerobic)	2,740,000	1,957,000
Dewatering (Vacuum Filter)	2,818,000	2,583,000
Sludge Hauling/Landfilling	467,000	373,000
Sub-Total	$ 38,808,000	$ 41,311,000
Noncomponent Costs[2]	10,866,000	11,567,000
Engineering and Construction Supervision	7,451,000	7,932,000
Contingency	7,451,000	7,932,000
TOTAL CAPITAL COSTS	$ 64,576,000	$ 68,742,000
ANNUAL O&M COSTS	$ 7,469,000	$ 4,219,000
TOTAL PRESENT WORTH COSTS[3]	$140,000,000	$111,347,000

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[1] See Appendix A for details of assumptions used in the cost analysis.

[2] Noncomponent costs include piping, electrical, instrumentation, and site preparation.

[3] Present worth computed assuming 20-year life at 7-5/8 percent interest rate (PWF = 10.0983).

TABLE B-13. ENERGY ANALYSIS (10^3 kwh/y) -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

CASE 1
PHOSPHORUS REMOVAL (EFFLUENT TP = 1 mg/L)

Process unit	Alternative 1-A one-stage activated sludge with alum addition (baseline)	Alternative 1-B PhoStrip	Alternative 1-C A/O
Low Lift Pumping	9	9	9
Preliminary Treatment	12	12	12
Primary Treatment	8	8	8
Aeration/Clarification	135	135	157[3]
PhoStrip (with Lime Addition)	---	55	---
Chemical Addition	8	---	4
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	4	4	4
Effluent Filtration	---	---	34
Gravity Outfall	---	---	---
Miscellaneous Structures	---	---	---
Thickening (DAF)	---	---	---
Digestion (Aerobic)	90	90	100
Dewatering (Drying Bed)	---	---	---
Sludge Hauling/Landfilling[2]	43	40	38
Total, 10^3 kwh/y	309	353	366
Unit Energy Utilization,			
kwh/1,000 m^3	447	511	527
kwh/1,000 gals	1.69	1.93	1.99

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle (see Appendix A).

TABLE B-14. ENERGY ANALYSIS (10^3 kwh/y) -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

CASE 1
PHOSPHORUS REMOVAL (EFFLUENT TP = 1 mg/L)

Process unit	Alternative 1-A one-stage activated sludge with alum addition (baseline)	Alternative 1-B PhoStrip	Alternative 1-C A/O
Low Lift Pumping	90	90	90
Preliminary Treatment	25	25	25
Primary Treatment	45	45	45
Aeration/Clarification	1,350	1,350	1,260[3]
PhoStrip (with Lime Addition)	---	105[3]	---
Chemical Addition	40	---	20
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	39	39	39
Effluent Filtration	---	---	325
Gravity Outfall	---	---	---
Miscellaneous Structures	---	---	---
Thickening (DAF)	170	120	150
Digestion (Aerobic)	900	900	950
Dewatering (Vacuum Filter)	95	75	75
Sludge Hauling/Landfilling[2]	417	397	374
Total, 10^3 kwh/y	3,171	3,146	3,353
Unit Energy Utilization,			
kwh/1,000 m^3	459	455	485
kwh/1,000 gals	1.74	1.72	1.84

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[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle (see Appendix A).

TABLE B-15. ENERGY ANALYSIS (10^3 kwh/y) -- 189,250 m^3/d (50.0 mgd) FACILITY[1]

CASE 1
PHOSPHORUS REMOVAL (EFFLUENT TP = 1 mg/L)

Process unit	Alternative 1-A one-stage activated sludge with alum addition (baseline)	Alternative 1-B PhoStrip	Alternative 1-C A/O
Low Lift Pumping	900	900	900
Preliminary Treatment	80	80	80
Primary Treatment	300	300	300
Aeration/Clarification	13,500	13,500	12,600[3]
PhoStrip (with Lime Addition)	---	210[3]	---
Chemical Addition	400	---	59
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	390	390	390
Effluent Filtration	---	---	3,100
Gravity Outfall	---	---	---
Miscellaneous Structures	---	---	---
Thickening (DAF)	1,150	750	1,000
Digestion (Aerobic)	210	210	240
Dewatering (Vacuum Filter)	850	650	650
Sludge Hauling/Landfilling[2]	4,170	3,970	4,170
Total, 10^3 kwh/y	21,950	20,960	23,489
Unit Energy Utilization,			
kwh/1,000 m^3	318	303	340
kwh/1,000 gals	1.20	1.15	1.29

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle (see Appendix A).

TABLE B-16. ENERGY ANALYSIS (10^3 kwh/y) -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

CASE 2
PHOSPHORUS REMOVAL (EFFLUENT TP = 2 mg/L)

Process unit	Alternative 2-A one-stage activated sludge with alum addition (baseline)	Alternative 2-B PhoStrip	Alternative 2-C A/O
Low Lift Pumping	9	9	9
Preliminary Treatment	12	12	12
Primary Treatment	8	8	8
Aeration/Clarification	135	135	157[3]
PhoStrip (with Lime Addition)	---	55[3]	---
Chemical Addition	8	---	4
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	4	4	4
Effluent Filtration	---	---	---
Gravity Outfall	---	---	---
Miscellaneous Structures	---	---	---
Thickening (DAF)	---	---	---
Digestion (Aerobic)	90	90	100
Dewatering (Drying Bed)	---	---	---
Sludge Hauling/Landfilling[2]	43	40	38
Total, 10^3 kwh/y	309	353	332
Unit Energy Utilization,			
kwh/1,000 m^3	447	511	481
kwh/1,000 gals	1.69	1.93	1.82

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle (see Appendix A).

TABLE B-17. ENERGY ANALYSIS (10^3 kwh/y) -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

CASE 2
PHOSPHORUS REMOVAL (EFFLUENT TP = 2 mg/L)

Process unit	Alternative 2-A one-stage activated sludge with alum addition (baseline)	Alternative 2-B PhoStrip	Alternative 2-C A/O
Low Lift Pumping	90	90	90
Preliminary Treatment	25	25	25
Primary Treatment	45	45	45
Aeration/Clarification	1,350	1,350	1,260[3]
PhoStrip (with Lime Addition)	---	105[3]	---
Chemical Addition	40	---	20
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	39	39	39
Effluent Filtration	---	---	---
Gravity Outfall	---	---	---
Miscellaneous Structures	---	---	---
Thickening (DAF)	170	120	150
Digestion (Aerobic)	900	900	950
Dewatering (Vacuum Filter)	95	75	75
Sludge Hauling/Landfilling[2]	417	397	374
Total, 10^3 kwh/y	3,171	3,146	3,028
Unit Energy Utilization,			
kwh/1,000 m^3	459	455	438
kwh/1,000 gals	1.74	1.72	1.66

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle (see Appendix A).

TABLE B-18. ENERGY ANALYSIS (10^3 kwh/y) -- 189,250 m^3/d (50.0 mgd) FACILITY[1]

CASE 2
PHOSPHORUS REMOVAL (EFFLUENT TP = 2 mg/L)

Process unit	Alternative 2-A one-stage activated sludge with alum addition (baseline)	Alternative 2-B PhoStrip	Alternative 2-C A/O
Low Lift Pumping	900	900	900
Preliminary Treatment	80	80	80
Primary Treatment	300	300	300
Aeration/Clarification	13,500	13,500	12,600[3]
PhoStrip (with Lime Addition)	---	210[3]	---
Chemical Addition	400	---	59
Nitrification/Clarification	---	---	---
Denitrification/Clarification	---	---	---
Chlorination	390	390	390
Effluent Filtration	---	---	---
Gravity Outfall	---	---	---
Miscellaneous Structures	---	---	---
Thickening (DAF)	1,150	750	1,000
Digestion (Aerobic)	210	210	240
Dewatering (Vacuum Filter)	850	650	650
Sludge Hauling/Landfilling[2]	4,170	3,970	4,170
Total, 10^3 kwh/y	21,950	20,960	20,389
Unit Energy Utilization,			
kwh/1,000 m^3	318	303	295
kwh/1,000 gals	1.20	1.15	1.12

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle (see Appendix A).

TABLE B-19. ENERGY ANALYSIS (10^3 kwh/y) -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

CASE 3
PHOSPHORUS REMOVAL AND NITRIFICATION
(EFFLUENT TP = 2 mg/L, NH_3-N = 1 mg/L)

Process unit	Alternative 3-A two-stage activated sludge with alum addition (baseline)	Alternative 3-C A/O
Low Lift Pumping	9	9
Preliminary Treatment	12	12
Primary Treatment	8	8
Aeration/Clarification	118	265[3]
PhoStrip (with Lime Addition)	---	---
Chemical Addition	8	4
Nitrification/Clarification	101	---
Denitrification/Clarification	---	---
Chlorination	4	4
Effluent Filtration	---	---
Gravity Outfall	---	---
Miscellaneous Structures	---	---
Thickening (DAF)	---	---
Digestion (Aerobic)	90	100
Dewatering (Drying Bed)	---	---
Sludge Hauling/Landfilling[2]	43	38
Total, 10^3 kwh/y	393	440
Unit Energy Utilization,		
kwh/1,000 m^3	569	637
kwh/1,000 gals	2.15	2.41

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle and credit for energy reduction due to recycle of nitrate (see Appendix A).

TABLE B-20. ENERGY ANALYSIS (10^3 kwh/y) -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

CASE 3
PHOSPHORUS REMOVAL AND NITRIFICATION
(EFFLUENT TP = 2 mg/L, NH_3-N = 1 mg/L)

Process unit	Alternative 3-A two-stage activated sludge with alum addition (baseline)	Alternative 3-C A/O
Low Lift Pumping	90	90
Preliminary Treatment	25	25
Primary Treatment	45	45
Aeration/Clarification	984	1,990[3]
PhoStrip (with Lime Addition)	---	---
Chemical Addition	40	20
Nitrification/Clarification	1,010	---
Denitrification/Clarification	---	---
Chlorination	39	39
Effluent Filtration	---	---
Gravity Outfall	---	---
Miscellaneous Structures	---	---
Thickening (DAF)	170	150
Digestion (Aerobic)	900	950
Dewatering (Vacuum Filter)	95	75
Sludge Hauling/Landfilling[2]	417	374
Total, 10^3 kwh/y	3,815	3,758
Unit Energy Utilization,		
kwh/1,000 m^3	552	544
kwh/1,000 gals	2.09	2.06

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle and credit for energy reduction due to recycle of nitrate (see Appendix A).

TABLE B-21. ENERGY ANALYSIS (10^3 kwh/y) -- 189,250 m^3/d (50.0 mgd) FACILITY[1]

CASE 3
PHOSPHORUS REMOVAL AND NITRIFICATION
(EFFLUENT TP = 2 mg/L, NH_3-N = 1 mg/L)

Process unit	Alternative 3-A two-stage activated sludge with alum addition (baseline)	Alternative 3-C A/O
Low Lift Pumping	900	900
Preliminary Treatment	80	80
Primary Treatment	300	300
Aeration/Clarification	9,352	18,664[3]
PhoStrip (with Lime Addition)	---	---
Chemical Addition	400	59
Nitrification/Clarification	10,100	---
Denitrification/Clarification	---	---
Chlorination	390	390
Effluent Filtration	---	---
Gravity Outfall	---	---
Miscellaneous Structures	---	---
Thickening (DAF)	1,150	1,000
Digestion (Aerobic)	210	240
Dewatering (Vacuum Filter)	850	650
Sludge Hauling/Landfilling[2]	4,170	4,170
Total, 10^3 kwh/y	27,902	26,453
Unit Energy Utilization,		
kwh/1,000 m^3	404	383
kwh/1,000 gals	1.53	1.45

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle and credit for energy reduction due to recycle of nitrate (see Appendix A).

TABLE B-22. ENERGY ANALYSIS (10^3 kwh/y) -- 1,892 m^3/d (0.5 mgd) FACILITY[1]

CASE 4
PHOSPHORUS REMOVAL, NITRIFICATION, AND DENITRIFICATION
(EFFLUENT TP = 2 mg/L, TN = 3 mg/L)

Process unit	Alternative 4-A three-stage activated sludge with alum addition (baseline)	Alternative 4-D Bardenpho
Low Lift Pumping	9	9
Preliminary Treatment	12	12
Primary Treatment	8	8
Aeration/Clarification	118	272[3]
PhoStrip (with Lime Addition)	---	---
Chemical Addition	8	---
Nitrification/Clarification	101	---
Denitrification/Clarification	24	---
Chlorination	4	4
Effluent Filtration	---	---
Gravity Outfall	---	---
Miscellaneous Structures	---	---
Thickening (DAF)	---	---
Digestion (Aerobic)	90	55
Dewatering (Drying Bed)	---	---
Sludge Hauling/Landfilling[2]	43	34
Total, 10^3 kwh/y	417	383
Unit Energy Utilization,		
kwh/1,000 m^3	604	555
kwh/1,000 gals	2.28	2.10

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle and credit for energy reduction due to recycle of nitrate (see Appendix A).

TABLE B-23. ENERGY ANALYSIS (10^3 kwh/y) -- 18,925 m^3/d (5.0 mgd) FACILITY[1]

CASE 4
PHOSPHORUS REMOVAL, NITRIFICATION, AND DENITRIFICATION
(EFFLUENT TP = 2 mg/L, TN = 3 mg/L)

Process unit	Alternative 4-A three-stage activated sludge with alum addition (baseline)	Alternative 4-D Bardenpho
Low Lift Pumping	90	90
Preliminary Treatment	25	25
Primary Treatment	45	45
Aeration/Clarification	984	2,585[3]
PhoStrip (with Lime Addition)	---	---
Chemical Addition	40	---
Nitrification/Clarification	1,010	---
Denitrification/Clarification	220	---
Chlorination	39	39
Effluent Filtration	---	---
Gravity Outfall	---	---
Miscellaneous Structures	---	---
Thickening (DAF)	170	90
Digestion (Aerobic)	900	550
Dewatering (Vacuum Filter)	95	75
Sludge Hauling/Landfilling[2]	417	333
Total, 10^3 kwh/y	4,035	3,832
Unit Energy Utilization,		
kwh/1,000 m^3	584	555
kwh/1,000 gals	2.21	2.10

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle and credit for energy reduction due to recycle of nitrate (see Appendix A).

TABLE B-24. ENERGY ANALYSIS (10^3 kwh/y) -- 189,250 m^3/d (50.0 mgd) FACILITY[1]

CASE 4
PHOSPHORUS REMOVAL, NITRIFICATION, AND DENITRIFICATION
(EFFLUENT TP = 2 mg/L, TN = 3 mg/L)

Process unit	Alternative 4-A three-stage activated sludge with alum addition (baseline)	Alternative 4-D Bardenpho
Low Lift Pumping	900	900
Preliminary Treatment	80	80
Primary Treatment	300	300
Aeration/Clarification	9,352	25,850[3]
PhoStrip (with Lime Addition)	---	---
Chemical Addition	400	---
Nitrification/Clarification	10,100	---
Denitrification/Clarification	2,100	---
Chlorination	390	390
Effluent Filtration	---	---
Gravity Outfall	---	---
Miscellaneous Structures	---	---
Thickening (DAF)	1,150	500
Digestion (Aerobic)	210	115
Dewatering (Vacuum Filter)	850	650
Sludge Hauling/Landfilling[2]	4,170	3,340
Total, 10^3 kwh/y	30,002	32,125
Unit Energy Utilization,		
kwh/1,000 m^3	434	465
kwh/1,000 gals	1.64	1.76

---

[1] See Appendix A for details of assumptions used in cost analysis.

[2] Energy equivalent of diesel oil in kwh.

[3] Including energy for internal flow recycle and credit for energy reduction due to recycle of nitrate (see Appendix A).

APPENDIX C

RESPONSE OF PROPRIETARY FIRMS

APR 16 REC'D

Air Products

Air Products and Chemicals, Inc.
Box 538, Allentown, PA 18105
(215) 481-4911

11 April 1984

Mr. Edwin Barth
U.S. ENVIRONMENTAL PROTECTION AGENCY
Municipal Environmental Research Lab
Wastewater Research Division
26 W. St. Clair Street
Cincinnati, Ohio 45268

Dear Mr. Barth:

Thank you for the opportunity to comment on the report, "Emerging Technology Assessment for Biological Phosphorus Removal" prepared by Roy F. Weston, Inc.

In general, we are pleased with the report and feel it accurately represents the state of the art of the A/O technology. I would like to comment in more detail in two areas. The first area concerns the discussion of the performance of the process to which I would like to add some thoughts. In the second area, cost comparisons, we feel strongly that the analysis given does not reflect the magnitude of cost savings available to users of A/O.

A. A/O Performance

The concentration of phosphorus in the effluent from a properly designed A/O plant will be mainly dependent upon the ratio of BOD to phosphorus of the wastewater treated. Our experience has shown when this ratio exceeds 10 to 1, an effluent soluble phosphorus of 1 mg/l or less can be expected. At ratios less than 10 to 1 the A/O process continues to function, but with increasing effluent phosphorus levels as the ratio decreases. One method of assuring performance to less than 1 mg/l total P is the combination of A/O with chemical precipitation. In this method, alum would be added either upstream to adjust the BOD:P ratio to the proper level or downstream to precipitate residual phosphorus. By combining A/O with chemicals where BOD:P may be less than 10:1, permit compliance is guaranteed while cost savings compared with the straight chemical approach will always be obtained.

B. Cost Comparisons

A major portion of the report is an analysis of the costs of biological phosphorus removal compared with chemical phosphorus removal. The large number of figures and tables does not seem justified since simplified assumptions and inconsistent methods of estimating the component costs were used. Specifically:

1. Some construction costs were reported to be estimated using the EPA I&A manual while other components are estimated using Weston in-house procedures. Cost estimates should be on an equal basis or at least some comparison of Weston methods with I&A manual methods provided. A discussion of the major differences among the processes and the impact on the cost would be very helpful to a designer considering using the A/O process.

2. The method of estimating the O&M costs is not given. No cost breakdown is given to indicate where differences in operating cost arise. The dosage and unit cost of chemicals are not given.

   Operating cost savings from lower chemical usage and less sludge production are a major incentive to prospective users of biological phosphorus removal plants. If this report is to accurately assess the value of biological phosphorus removal, additional discussion and further detail is needed in this area.

3. No consideration is given to retrofit of existing activated sludge plants. Retrofit of A/O can often lead to large operating cost savings over the life of the plant.

4. The relative cost advantage of biological phosphorus removal is made to appear small by adding other non-phosphorus removal related components to arrive at a "total" cost figure.

5. The cost of tertiary filters appears high. For example, the actual bid installed cost for an Enelco brand filter for the City of Largo (15 MGD, bid November 1981) installed in an existing concrete shell was $850,000. The figure given in the report for a 5 MGD case including concrete is $1,300,000.

6. It is assumed that the A/O process will require effluent filtration to meet a 1 mg/l total P standard. A much less expensive method would be to supplement with chemicals.

   It should be recognized that chemical phosphorus removal processes will also produce a phosphorus rich sludge and may require effluent filters to meet 1 mg/l. For example, a typical activated sludge plant treating

> 150 mg/l BOD (after primaries) with an overall sludge yield of 0.8 lb. solids/lb. BOD removed will produce 1000 pounds of waste sludge per million gallons. If alum is added at a dosage of 15.0 mg/l (as Al^{+++}) to precipitate 10 mg/l phosphorus, an additional 437 pounds of sludge will be made totaling 1437 pounds of waste sludge. This will contain 75 pounds of phosphate resulting in a sludge phosphate content of 5.22%. Solids contained in the effluent will reflect increased phosphorus content.

Ed, thanks for your consideration in allowing me to comment on this report. I hope this will be of value to you.

Sincerely,

David J Krichten

David J. Krichten
Technical Specialist
Environmental Products Department

DJK/cah

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MAR 14 REC'D

March 9, 1984

Mr. Ed Barth
Chief Biological Treatment Section
Wastewater Research Division
United States Environmental Protection Agency
Municipal Environmental Research Laboratory
Cincinnati, OH 45268

Subject: Emerging Technology Assessment of Biological Phosphorus Removal

Dear Ed,

I received the copy of the Technology Assessment Document which you sent to me on January 20, 1984. I have reviewed this document and as we discussed by telephone, wish to transmit to you various concerns that Eimco Process Equipment Company has regarding certain areas of the report.

The comments that we wish to make here fall into three general catagories. These catagories relate to the operation, performance, and cost of the Bardenpho Process. We believe that judgements and analyses have been made which are inappropriate and outside the context of the original objectives for the technology assessment of biological phosphorus removal as explained to us.

First, the summary document generally presents the judgement that the Bardenpho process is applicable to and should be considered only in situations where denitrification is a requirement in addition to phosphorus removal. We strongly object to this judgement and believe it is both incorrect and fails to recognize key process related issues affecting efficient biological phosphorus removal. It should be abundantly clear from the presentations from Eimco and others that control of all electron acceptors, especially nitrate, is a critical prerequisite to proper fermentation performance and thus efficient biological phosphorus removal. The introduction of nitrate to the fermentation reactor must be avoided if proper fermentation and phosphorus release are to occur. The Bardenpho Process does not evade this issue inasmuch as total nitrogen control is accomplished within the Bardenpho flowsheet. Eimco believes that the Bardenpho Process provides a positive, reliable configuration which assures that nitrate cannot deteriorate biological phosphorus removal. No other configuration provides this assurance. The fact that Bardenpho provides nitrogen removal, even when such is not required, provides no basis to conclude that Bardenpho is inappropriate for applications requiring only phosphorus removal.

The judgement made by the Summary Document that Bardenpho is not applicable in situations not requiring nitrogen control, seems to be based on the assumption that a two or three stage system must be less expensive than a five stage system. This assumption is erroneous since it failes to recognize that a rational process design will be based on providing the necessary SRT to provide the required effluent quality in terms of BOD and ammonia. As such the reactor volume should be nearly equalivant regardless of the number of stages employed. Eimco believes that it is best to divide that reactor volume into five stages to provide nitrogen control for reasons discussed above. The difference, therefore, relates to the number of inner partition walls and the specific function of the subreactors created by location of those partition walls. With that in mind, it seems clear to us that a five stage reactor, which accounts for the potential of nitrate formation during various seasons or operating conditions at a full scale facility, and develops energy and akalinity restoration benefits as a result of denitrification, is the preferred configuration for applications requiring phosphorus removal.

Now it is true that many of the Bardenpho Process designs in the United States have been based on long SRT operation. The reason for this relates to the fact that most of these situations involve applications requiring total nitrogen control to levels of the order of 3 mg/ℓ TN. With the relatively longer SRTs required to assure achieving less than 1 mg/ℓ ammonia, and the anoxic volume required to achieve an effluent of 1-2 mg/ℓ nitrate, it becomes obvious that utilizing only a slightly larger SRT could result in the production of a stablized sludge eliminating the need for additional costly digestion and eliminating concerns of phosphorus release during the digestion process. We would stress, however that this is a detailed design decision made by the engineer outside the scope of whether a two, three or five stage system is employed.

Therefore, Eimco would like to see this judgement and statements concluding where Bardenpho's "greatest market potential exists" removed from the Summary Document. For your reference, the most obvious examples of this appear on page V, 14, & 53.

Secondly, there is a general implication and specific statements made to the effect that the Bardenpho process capability to achieve effluent phosphorus values of less than 2 mg/ℓ is not demonstrated. The only two operating Bardenpho plants in North America disproved this statement. The Kelona, British Columbia facility, which was reported on at both sessions of this workshop, has consistently produced an effluent of less than 1 mg/ℓ phosphorus after its initial acclamation period while the Palmetto, Florida Bardenpho facility presently averages 1.5 mg/ℓ effluent P without chemical addition. This level of performance at Palmetto can be directly attributed to the fact that the influent wastewater BOD concentration is unusually weak for domestic wastewater and less than 50% of the design value. Labeling the Bardenpho process as incapable or unproven in producing effluent phosphorus values better than 2 mg/ℓ would seem to not be justified. We are concerned that this statement in the Summary Document will be taken out of context by others and interpreted in far too general a context. To prevent this, we respectfully request that statements to this effect be removed from Summary Document. Such statements are found, for example, on pages 14 & 28.

Thirdly, the summary document presents numerous cost analyses of the various biological phosphorus removal flow sheets. In the first place, the cost analyses again relegate Bardenpho only to those applications requiring denitrification with no consideration given to the technical and economic benefits of Bardenpho in other applications evaluated. More importantly, we have serious reservations about the validity of the cost analyses performed. For example, the Bardenpho Process was designed arbitrarily and based on nominal detention times. The dentention times arbitrarily selected are, for the most part, higher than that normally found in U.S. Bardenpho Process designs based on rational design approaches. Therefore, we feel that the results of these cost analyses, particularly where the Bardenpho Process is involved are neither accurate for the general case nor even for the example selected for this analysis. Actual bid prices taken on several commercial plants during the past one - two years testify to the inaccuracy of the cost analysis.

Our concern, of course, is that these analyses will be used and abused as consulting engineers attempt to evaluate relative cost and performance effectiveness of the Bardenpho Process. Process selection decisions will be made on the basis of these analyses and these decisions may, in many cases, be in error. Doubting that process selection decisions will be made based on these cost analyses is naive. There are many consulting engineers in the United States today who utilize general cost information such as that found in the EPA I&A Technology Manual and the infamous CAPDET program. This is done because it is not only the easiest thing to do, but also readily accepted since the cost information is generally associated with having been developed by various agencies of the Federal Government such as the EPA and The Corps of Engineers.

Therefore, Eimco believes that presenting generalized cost information such as that presented in the Summary Document is risky, inappropriate, and in fact serves no real benefit. On the other hand, there is an unfortunate opportunity for misuse of that information. Thus Eimco has a strong preference to have this cost information removed from the Summary Document.

In addition, there are several statements made in the Summary Document which we believe are inaccurate. Without trying to be too picky, we would just highlight two of them here. First, on page 56, a statement is made that "some of the failures associated with the Bardenpho System have been related to low COD:TKN ratios in the feed to the system". This statement is really not accurate. In our opinion, the COD:TKN ratio was not a problem at all, but rather the inadequacy of the design to account for the quantities of nitrate produced and reduced in the system. As such, there was excessive residual nitrate in the system which deteriorated phosphorus removal capability. As stated earlier in this letter, this is precisely why Eimco feels so strongly that biological phosphorus removal flowsheets must be capable of total nitrogen control.

The authors of the summary document briefly discussed operation and maintenance considerations on page 20. In that section, they state that the Bardenpho Process is more complicated than PhoStrip or AO since the former involves both phosphorus and nitrogen removal. We simply can't understand how the author can come to that conclusion with any understanding of the various mechanisims operative in a biological phosphorus removal flowsheet. I'm sure you can understand our difficulty with this conclusion, considering our conviction that a five stage Bardenpho design is operationally stable and forgiving since there are no swings in nitrification or denitrification on a daily or seasonal basis. Such may not be the case for process designs based on the ragged-edge of nitrification SRT values with inadequate capability to respond to various denitrification requirements. The inherent stability of the Bardenpho Process is even more obvious in situations where long SRTs are employed to achieve sludge stablization. Thus, we find the statement that Bardenpho is more difficult to operate to be not only unjustified, but actually opposite to the real situation. We trust that the authors will have no problem in correcting this conclusion in their report after considering the process related aspects of each of the flowsheets more carefully.

Ed, I trust that the comments contained herein will find acceptance by yourself and the authors of the Summary Document. I also understand that the Document is being reviewed by two extramural parties. I am hopeful that these parties will also bring some of the issues raised in this letter to the attention of the authors for consideration. I will look forward to hearing from you on these issues and will be more than happy to discuss them in more detail as necessary.

Sincerely yours,

Eimco Process Equipment Company

David DiGregorio

David DiGregorio, Manager
Process Marketing & Development

DD/ms

Comments on "Emerging Technology Assessment of Biological Phosphorus Removal"

G.V. Levin, Biospherics Incorporated

1. Abstract - p.v., first paragraph, why not mention effect of I + A funding and construction grant program on present worth costs to the community? These programs have major impact on capital costs to the community, particularly in comparing the new processes, which are eligible for I + A, to the baseline process which it is not.

2. Table 5, p. 37, same as 1. above.

3. Fig. 5a, p. 43, same as 1. above.

4. Table 6, p. 38, should compare apples to apples: either PhoStrip at 2 mg/l TP effl. or alternatives at 1 mg/l TP effl. I think the latter is more appropriate since most effl. stds. are 1.0 mg/l T.P.

5. Table 6, p. 38, since $ crossover for PhoStrip occurs soon after 5 mgd is passed (see p. 53, first bullet) why not extrapolate point where crossover in present worth occurs and show it in Table?

6. p. 3, 9th line from bottom, after "Figure 1," strike "or" and after "primary effluent" insert "or recycled stripper sludge."

7. p. 3, bottom line, add "A variety of other PhoStrip modes has been described by Biospherics, ranging from elimination of stripper tank through use of existing tankage for sludge stripping to a no chemicals version, but none has been demonstrated full-scale."

8. p. 3, 18th line from top, delete comma between "Biospherics" and "Inc." (ibid wherever else occurring).

9. p. 3, line 22, after "activated" add "air or oxygen."

10. p. 4, Figure 1, Direct Sludge Recycle is given as "(0.2 to 0.3Q)". I think it should be stated "(0.2 to 0.5Q)" since the process has frequently been operated at 50 percent direct return sludge. This change would require corresponding change for "Phosphorus-Enriched Sludge" to "(0.2 to 0.5Q)." Also, "Elutriation From Either:" should be "Elutriation From Any of:" to be grammatical.

11. p. 11, 12th line from bottom, after "selection," I suggest insertion of "or inducement." This is because there is still no definitive word on whether the population is selected or whether P-uptake and release results from enzyme inducement in the general biota. The same addition would be made three lines below this where "selection" appears again.

12. p. 15, 13th line from bottom, if suggestion 10 above is accepted, change "0.3" to "0.5."

13. Reference 4, change "Experimentia" to "Experienta."

14. Reference 11, Change "Tarmy" to "Tarnay."

15. Reference 13, change "Masse" to "Maase," and "J.J. Kish" to "A.J. Kish," and delete comma after Biospherics.

16. Reference 31, remove comma after "Biospherics."